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Robots Operating in Hazardous Environments

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ROBOTS OPERATING IN HAZARDOUS ENVIRONMENTS

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Notice

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Meet the editor

Dr. Hüseyin Canbolat was born in Adana in 1966. He received his BS and MS degrees from the Middle East Technical University, Ankara, Turkey, in 1989 and 1993, respectively, and PhD degree in Electrical Engineering from Clemson University, Clemson, SC, USA, in 1997. After his PhD studies, he joined the Department of Electrical and Electronic Engineering at Mersin University in 1998. In 2012, he joined the Department of Electrical and Electronic Engineering, Ankara Yildirim Beyazit University, Ankara, Turkey. His research interests include control systems with applications to robotic and mechatronic systems, MEMS, energy systems, signal processing, measurement, and instrumentation. He is a senior member of IEEE.

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Preface

Robots have been employed in industry in the form of a human arm more than half a century. PUMA by Unimation is an early example of such manipulators. Robot manipulators have become one of the main parts of the conveyor belts in automotive industry.

In the last several decades, robotic systems have been employed in hazardous areas. Hazards may be in the form of direct dangers to humans, or the environment may have risky agents. The exposure to dangerous chemical substances, the biological agents that can risk the health, and the demanding environments in which the human abilities cannot be sufficient are among these risks.

Examples of such environments include fire, radioactive leakage, earthquake debris, clearing the land mines, preventing terrorist attacks, space, excavations, oil refineries, and chemical plants.

One of the major justifications for employing robots is to protect people from handling hazardous materials and from working in dangerous environments. Robots are used in dealing with explosive or combustible chemicals and handling radioactive substances, in nuclear plants, where people are in danger of injury or killing, and are exposed to unhealthy conditions.

The book is organized in five sections. The first section is about demining operations. This chapter reviews the robots, which are used for humanitarian demining operations. The second section presents a UAV equipped with SDR-based GPR technology that can detect the land mines. In the third section, an advanced tele-robotic application in a nuclear plant is presented. The next two sections may be seen unusual in a book on robotic systems in hazardous environments, in the sense that these sections deal with the protection of robots operating in dangerous places and the occupational health and safety issues in workplaces where robots and humans work together. The fourth section deals with protecting robots in hazardous environments from malfunction and damages. The fifth section investigates the rules that prevent accidental harms and damages to humans caused by the robots in a workplace, which are not really dangerous.

I hope the book will provide better understanding of robotic operations and new insights for the readers.

Dr. Hüseyin Canbolat
Yildirim Beyazit University,
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Section 1

Humanitarian De-mining

Chapter 1

Robots for Humanitarian Demining

Manjula Udayanga Hemapala

Additional information is available at the end of the chapter

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Abstract

More than 100,000,000 anti-personnel mines have been laid in deferent part of the world by terrorists or government forces. The mines are cheapest weapon, built to make horrible injuries, affecting active people, with major falls-off into economic growth. Therefore, after or during a war demining is a big technological problem which needs to address by the governments. All demining activities can be classified mainly in two different ways, military demining and humanitarian demining. Main objective of military demining is to make a quick safe path for troops and may be 80% clearing is enough for them. On the other hand, humanitarian demining target is to clear 100% to ensure the use of lands by people who are not involved in the conflicts for their day-to-day activities including farming. Mainly humanitarian demining has two tasks: detection and removal. Still the use of robots is questionable in this regard. Mainly robots work well for clean and reliable tasks. When the price to performance ratio is too high, they are academic toys. This chapter presents the overview of the available robotic technologies with a depth comparison between them by considering the appropriateness to the local context.

Keywords: humanitarian, demining, autonomous, remote control, sustainability

1. Introduction

The landmines are weapons developed to be deployed near or under the ground to explode when it is contacted by a person or a vehicle. Basically landmines can be dived in to two: AP anti-personnel and AT anti-tank landmines, depending on their target and the cost. Both were used by the military personals to protect their zones from their enemies. Because of their low cost and the easiness of the deployment, landmines will be spread in the land. This will stop any further use of these valuable lands for civil purposes.

On these humanitarian grounds, the Ottawa Convention [1, 2] prohibits their use, manufacture, trade and stockpile, and requests their destruction. This convention is promoted by the United Nation and ratified by several nations. Still few countries are not the members of this convention as they are involving war between different communities in their countries. Therefore, landmine is a typical problem for the developing and under developed countries.

Demining can be classified in two, depending on the problem definition [3].

- The military minesweeping: to achieve fast clearing with acceptable reliability to open a safe passage for military personals to enter their battlefield;
- Humanitarian demining: to achieve 100% clearance of the ground at acceptable cost.

The present humanitarian demining process does not addressed the actual ground situations and not giving a viable and acceptable answer [4]. Lot of research and efforts have already been undertaken but cannot see a viable answer when considering the ground situations. The idea is to find a long lasting and an acceptable solution by a bottom-up approach with the local technological know-how. This will help expanding the local people consciousness to become the master of their own ongoing upgrading, by qualifying commonly used devices and techniques and turning them towards humanitarian demining duties.

In the current context only manual mine clearing is used by deminers as an acceptable methodology while armed forces are using high cost mechanical mine clearing. The ‘robotic solution’ becomes a highly engineering job which is depending on imported devices where the know-how is not available. The increasing cost of the sophisticated devices incorporated in to the robotic devices making very high initial investment and low return on investments. Therefore understanding the actual background is required before trying to solve forcefully as a technology driven issue.

For such purpose, the present investigation tries to acknowledge the main conditioning peculiarities through solution appropriateness to local context. In this context, the following conditions should be recognised:

- Local socio-political implications should be removed or neutralised before applying the technical solution.
- The humanitarian demining outfits should assure the fit-for-use land operation with the community involvement at the standard decentralised level.

The two aspects suggest series of assumptions where necessary to study in the present context. First, no abstract developments are considered; on the contrary, proper investigated measures are dealt with, deeply rooted on the local historical frames. Second, the factual evidence of behaviours is deferred to results, and these are consequence of achieved benefits. Third, the routine job shall achieve the final objectives with minimum damage, and finally, the techniques and workflow should organise with well-understood know-how.

Although there are millions of people living in landmines affected countries, the size of the landmine problem is not yet well defined. Quantifying the landmine size is a difficult task as no reliable information or indicators. After the Second World War, the developed countries within Europe also affected by landmines. But recently, landmines are the major issue for developing countries where ethnic conflicts have taken place. Landmines have been used from centuries to protect valuable lands. Their present use, because of the low cost made them suitable for putting everywhere without any restrictions during civil conflicts, typically in developing countries.

The landmines stay in the ground even after the end of the conflict in active state until the land is cleared. This will obstruct the free movement within the affected areas whether the area is agricultural or not. As the landmines are remaining for years on the land, the important resources linked to these areas cannot be used. Therefore, landmine removing with 100% clearance is a necessary duty.

Therefore, landmines influence the development indices in both economic as well human. The mine-affected countries' economies are badly affected by loss of land, loss of human lives, loss of production, etc. Lot of indirect factors such as social services, education services, health services and transporting goods are also affected [5]. The human development is also heavily affected by landmines because of direct factors as well indirect factors. Human freedom index (HFI) is heavily affected by the inability of the freedom of the movement. Therefore reducing the impact on landmines is very important in developing countries.

Landmine issue should not be considered as an isolated problem as the developing countries are facing some other problems in the same scale such as tsunami, dengue, accidents, etc. The demining is very extreme very slow process with the existing methodologies and strategies.

Today, there are several industry level marketed products which replacing the men from the mine filed. And also there are robots with intelligence and self-organising facilities but they are not well fitted to the actual filed. However, the strength of the industrial revolution is depending on the entire workforce with pre-established jobs allocation according to the relevant knowledge. Only in such a situation, the technologies reach the real suitability, and lead to higher incomes for the populations involved. The analysis is not continued, keeping mainly the following points:

a. The selected technologies must provide special equipment, with a task oriented to the duties and a uniformity adapted by the operators;

b. The pre-establishment of the workflow should detail the work cycles and the standard achievements, and specify the rules of protection of failures in course;

c. The instruction and training of operators aims to optimise workflows outside the process, especially to avoid the emergence of risky commitments;

d. Efficiency comes from organised routine work, fulfilled by the diligent activity of the workforce, in accordance with assigned tasks;

e. The local public administration is entitled to the authority to promote the mine clearance service, and the community involved is very concerned.

Basically, the description assumes the commitment of neighbouring political societies, deal with terrorist damage, react automatically as soon as the incursions are made, and immediately put into action the recovery processes, resorting to the forecasting equipment and the pre-established schedules. The legal framework does not require any updating, unless the usual elements of solidarity. Technical support should be developed in accordance with the ideas of the (original) industrial organisation, focusing primarily on the effectiveness of job placement procedures, in parallel with the diligence of hired labour.

The chapter is organised as follows. The present chapter provides the introduction with covering the problem definition, the technical and other challengers that need to be faced by the demining demands. Section 2 basically specifies the literature review, including the current demining issues, the role of the robots in humanitarian demining, the existing demining technologies and agricultural technologies for demining, safety issues and lessons and suggestions. Section 3 deals with the proposed sustainable solution which includes the functional design, architectural design and operational techniques. Final section discusses the conclusion with the suggestions for future research directions.

2. Literature review

This section basically specifies the literature review, including the current demining issues, the role of the robots in humanitarian demining, the existing demining technologies and agricultural technologies for demining, safety issues. And finally, some lessons and suggestions for future improvements are added.

2.1. Landmine classification

The removal and the destruction of mines safely from the sites are very important for any country to recover from the threats. However, this tedious task involves money, time and risk. Anti-personnel (AP) mines are harmful because of their unknown characteristics such as small in size, different explosive loads and different triggering. Landmines can be activated by:

- Pressure
- Tripwires
- Remotely

Some of the landmines used in battlefield [6] are listed in **Figure 1**.

Mines may have been in place for many years in the battlefield. With the time, they may be corroded, mixed with water, mud or dust and they may activate in unpredictable ways. Some mines were moved into a new location and buried deep in the soil by making the demining process more tedious work. Deeper mines may not activate but may later detonate when the ground is soft. Modern landmines are made from non-metals with advanced technologies which prevent detecting using metal detectors.

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Figure 1. Types of landmines used in battlefield.

2.2. Landmines clearance basic processes

The basic process of landmine clearance consists with different tasks [7, 8]. Basically they are

- Map the mine field by data collections
- Prepare the identified land for clearance
- Identified the individual mines within the marked area by a mine detection equipment
- Clear the detected mines by removing and destroying

A clearance is a process that needs a proper methodology which considers technological sustainability, economical sustainability and social sustainability as well as weather and ground conditions. It is necessary to associate this process with social awareness to reduce the unarmed civilian causalities. Locating the mined land will help to separate the danger from people and to make the land for the usage of the civilians.

2.3. Economical aspects of demining

The economic aspect is more important since most of the affected countries are Third World countries. Most demining countries are receiving funding from international organisations for their demining operations. By helping to secure funding longer, tackling the problem of landmines as a development problem would also help to see the problem under a different perception, allowing for a faster and more efficient approach. As the fear of mines affecting local communities and not the actual presence of mines is evident, areas considered to be mined pose a certain level of risk. Therefore, the 100% mine clearance requirement could be changed to a lower degree of safety [9].

Since demining has a major influence on development, technology for humanitarian demining also plays an important role in development. The importance of the role of technology in development is widely recognised. Science and technology play a fundamental role in the development process, as demonstrated by the industrial revolution. After 1820, one-sixth of the world's population reached a high level of income through consistent economic growth and technology has played a vital role.

In fact, one of the main differences between rich and poor countries is their tendency to innovate new product or services. Inventors or researchers in poor countries do not invent new product because they know that they will not be able to recover those large fixed costs of developing new products. Other technologies developed in other countries can help them to introduce new ideas or tools to make it best fit for their ecological reasons. Therefore, investing in technological capabilities is believed to be one of the key actions that rich countries can take to end poverty in developing countries. In fact, the increase in investments in technological capacity and not only increase the amount of financial capital per person, but also the quality of the technology incorporated in the transfer and the corresponding degree of adequacy [10].

Rapid economic development requires high technical capacity for entire society. However, that technology should be suitable to the local context. Home grown technology is needed in every sector in developing countries with the help from developed countries for adapting the local needs in areas ranging from energy production and use, construction, natural hazard mitigation, disease control and agricultural production as well as demining [11–13].

Despite peace, the remnants of the protracted civil wars in the third world continue to disrupt people's lives, posing a physical as well as a psychological threat to those internally displaced persons (IDPs) that have returned, and contributes to the continued displacement of those that remain displaced. Landmines and unexploded ordnance (UXO) lie amidst a multitude of complex and interlinking problems. When IDPs return, they not only find their land mined, but their homes, businesses and commercial centres destroyed; their agricultural tools, fishing equipment and boats, livestock and possessions lost or stolen, and a political and social welfare system struggling with the consequences combined with a dependency on outside assistance, which was high even before the conflict began.

Demining is a process which is consuming huge money. It is estimated that the current demining rate is slower than the laying rate. It seems an endless war with endless demining. Therefore, to take an effort to stop further use of landmines is very important task. Otherwise, the ongoing humanitarian demining activities result mostly ceaseless, with no practical falls-off, unless the minesweeping could become a cheap, safe and fast operation, so that the mining would be reduced to almost useless deterrent.

2.4. Reference demining technologies

2.4.1. Manual demining method

Manual demining is a procedure in which mines are manually detected by any kind of detection method and neutralised by human deminers. Manual demining is not safe but it is effective than other methods with low cost. Rake method is the one of the lowest procedure that can be used for demining. There are three types of rakes used in the demining field, heavy rake (Harrow), metal light rake (Brush), and plastic light rake (Brush). Categorisation words such as heavy and light would not describe their function and describe only the weight of the equipment. The heavy rake is used where the ground is tough and the light rake is used in loose soil.

Safety and performance is based on the design of the rakes. Rake has a long handle to keep the deminer at a safe distance during an accident. This work is a repetitive task and it requires a considerable effort. The two-pronged rake has a good performance by loosening the rigid soil and raising the mines out of the ground. The brush rake is used to move the floor towards the deminer. There have been no accidental initiations while using the brush rake, which is believed to be inherently 'safer'.This is a cost-effective method comparing other existing methods. Still it is dangerous for the deminer as he is not in a good safe area.

2.4.2. Mine detection sensor technologies

There are many technologies tested for demining [14]. The well-known techniques, their principle of operation and the current state of usage are described in the following texts. In this section, the short survey describes the sensing technologies that will help full to humanitarian demining in the present as well as in the future. Basically, sensing technologies can be divided into two categories as shown in the **Figure 2**. Some of them are briefly descried in latter sections [15, 16].

Strength and limitations of different sensor technologies are presented in **Table 1**.

Sensitivity of the mine detection animal is much higher than the man-made detector. Specially trained rats, dogs could be used to detect the explosive [17]. Most of these animals can work all most all types of terrain with few constrains such as time limitation. Because most of these animals cannot work for long time efficiently as they may fed-up with their work after few hours of work. Effectiveness of mine detection by animals depends on their training and the environment they are working. Anyway, this can be a costly option for most of the affected countries.

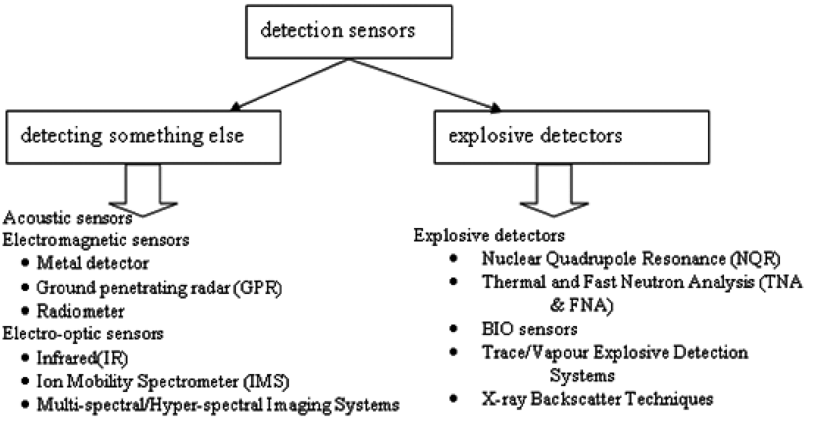

Figure 2. Detection sensor technologies.

	Strengths	**Limitations**
Acoustic sensors	Remote sensing Low false alarm rate Detection non-metallic mines easier	Mainly detection of anti-tank mines Limitation in heavy vegetation
Metal detector	High robust and reliable cheap	Only for metallic mines Sensitivity and detection depth will vary
Ground penetrating radar	Capable of detecting non-metallic objects Can provide the depth information Low power requirement	Depending on the ground condition Resolution will vary with depth penetration
Radio meters	Suitable for the detection of mines placed on the surface of the ground with light vegetation	Not possible to detect buried mines
Infrared	Possible to scan large area	Not possible to focus on single mine

Table 1. Comparison between different sensors.

2.4.3. Mechanical demining equipments

Mechanical approaches rely on the use of motorised approach. Basically those machines are not specifically designed for the said task. Some of them have been adapted from military vehicles or from agricultural vehicles [18, 19]. The mechanical approach is fast and well suited for making a cleared passage, but still cannot achieve the precision of humanitarian demining and safety standards. And also this method is not an environmentally friendly solution. Mechanical methods have emerged with their own strengths and weaknesses. Mechanical machines do not destroy all mines in a contaminated area but it can be pushed the anti-personnel mines away from the passage. This will make them more dangerous as the mines can be buried more deeply or partially damaged. There are different techniques used by demining agencies to clear the mine field such as flail systems, tiller systems, combined systems and agricultural systems (**Table 2**).

	Advantages	**Disadvantages**
Flail systems	The machines work on the principle of using force to detonate or destroy mines. The concept is quite simple	Clearance accuracy and efficiency is depending on the speed of the flail, direction of travel, and weight of the hammers
Tiller systems	Able to reach landmines as deep as 50 cm. It uses speed, impact and mass to destroy mines as they move on the field	Limits their effectiveness in some types of terrain, and maintenance costs are high
Agricultural systems	Agricultural systems can adapt to demining task with little change with low cost	Till the cost is high

Table 2. Mechanical demining systems.

All above techniques do not solve the world demining problem. They fulfil only one part of the problem. They cannot work alone in the field. They must do the work after some clearance or after they cleaned some other instrument should follow to check the field.

2.5. Robots and humanitarian demining

Demining community would like to use teleoperated robots or fully automated robots for their work as it will enhance the safety. Applying the technology should be done with a balance between the cost and the efficiency. Therefore, a complete cost analysis should be done for the optimisation without sacrificing the efficiency and the safety. Properly sized robotic solutions with suitable mechanical structures are well suited for developing countries with targeting high safety and productivity. Robotic technology with sensors, semi or autonomous navigation and machine intelligence are the present challengers which are faced by the demining industry. Furthermore, the use of many robots such as swarms and coordinating them, using Multi Agent Systems (MAS) will improve the productivity. Anyway, the guarantee will not be there for those robots when they are working in the hazardous area. Therefore, correct evaluation and analysis should be done in order to find the best-fit solution for the local community.

Still robots are well for clean environments [20–26]. However, demining area is not flat and it consist lot of obstacles. The normal robots cannot move freely in this kind of environments. Clearly, it is a challenging task to design a universal solution that is applicable for different field with lot of other constraints. And also these highly technical robots or machines need very well trained people which may difficult to find in most of the war-affected countries.

Due to the complexity of this clearance process, the international community should work together with the affected country in order to find a sustainable solution with enhanced effectiveness, high reliability and safety.

2.6. Safety issues

The demining work mainly depends on manual removal by humans. It gives serious safety issues, as human operator is not out of the dangerous area. For increasing safety mechanical demining machines with remote control ability and autonomous robots with autonomous detection capability have introduced [27–33]. In these cases, the human operator is safe but not the machine. It is very important to consider the safety of the human operator and the machine itself. And also remote control robots faced some safety issues with control because they are going to work with variety of environmental conditions. Therefore, it is better to propose a system which can remove mines safely without prior detection phase. Robot aided minesweeping (RAMS) is going address this task [34, 35].

2.7. Lessons and suggestions

The state-of-the-art survey provides the background information on humanitarian demining with the assumptions of our investigation. It could render terrorist operations ineffective and within a very short period of time but it is a very difficult task. According to the literature review, it is found that today no clearing process guarantees the required effectiveness, in terms of cost-to-result performance. The elaborated techniques each have their own merits and could be retained in specific situations:

- the mechanical demining is a useful technique for military mine clearing to establish a safe route for their troops;
- the manual clearing using rake techniques with or without detecting devices is the only left option when the field is vegetated with irregular ground.

However, the problem here is to clear agricultural land right after the terrorism is over for the farming activities. The efficiency is highest important thing with safety and reliability. Engineering solution for this problem should assure the safety with low cost. Therefore, front mechanism for neutralising the mines should be managed by remote control with assuring the highest adaptivity and flexibility due the direct human overseeing. The main constraints, for the development successfulness, distinguish a series of accomplishments.

However, the basic problem here is to clean up the agricultural land after eliminating terrorist activities from the field. Highest efficiency is a fundamental requirement for an engineering solution with acceptable safety and reliability. Fully autonomous robots with high cost could replace by introducing remote control with greater adaptability and flexibility with human supervision. The successfulness may depend on

- the infrastructure which should be managed effectively with the local society for promoting and steering the initiatives.
- the proper way of workflow setting to achieve a higher productivity in the mine clearing with pre-defined targets;
- the design and development of the demining outfits which is directly derived from local know-how;
- the assessment and establishment of the task schedule in strategic, tactical and execution levels for the bottom-up clearing approach.

This work is addressing the engineering issues, examines the third achievement, with due concern from the second (analysing workflow diagrams, focusing on in-service alarm/recovery patterns) and the fourth (using results from the simulation, with an explanatory purpose in the accumulation of knowledge of the process).

According to the above outlined implementation constraints, the development of the consistent task-oriented outfits would be the principal objective of the present day investigations. The qualifying requirements to be

- the cost containment of the basic equipment and maintenance charges;
- the shared knowledge of the technologies involved and full confidence in their use.

The favourite choice lies within the agricultural machines which are widely available and purposely can be changed their structure for the use of demining. The local market makes extensive reference to simple and chip equipment, for multi-task machines, so that there is a great possibility of finding basic devices which can be transformed easily into mine clearance equipment by adding special-purpose kits. The choice goes, perhaps, without saying, once recognized the restrictive inferences that cannot be left aside. However, real development requires a series of actions such as the following:

- To characterise the selected agricultural machine with duty-driven fixtures to achieve the required demining capabilities;
- To design and implement the selected manipulators, preserving the machine technological consistency, with shared know-how for keeping the maintainability;
- To define and schedule the programme flow charts in order to improve the productivity in strategic, tactical and execution levels with specified targets, thresholds and timings;
- To appraise and check the performance in all areas such as safety, effectiveness, and reliability with considering the unexpected failures.

The whole process is a standard engineering activity which is to be fulfilled by providing the details of the explanatory developments covering

- strategic horizon: duty-steered functioning to prove the suitableness and appropriateness of the selected technology;
- tactical horizon: occurrence-driven performance to help selecting optimal procedure to achieve the continues running with highest productivity;
- execution horizon: anomaly-coerced evolution with on-process decision patterns to show the adaptivity and flexibility of the operation.

In fact, old industrial productivity remains at the level of out-of-process configuration (scientific paradigms of job assignment), and this would prove to be totally flawed outside manufacturing facilities with the flow-store organisation. The current flexible productivity of automation comes from the real-time management of standard tactical plans and unforeseen anomalies (intelligent task-oriented paradigms), and this can be governed by fully autonomous government blocks factories) or schemas in mixed mode (with in-line and/or remote control operators to direct the front effectors). The all leads to the job-shop organisation, and can readily be extended to the loosely structured environments, basically, referred to as robotic implementations.

The general principles are the well-known methodologies in the modern engineering with the above requirements. This helps the present investigation to be more challenging with motivated objectives.

Special-purpose mine clearance equipment and procedures are intended to be explanatory opportunities and equivalent equipment/programming may be devised with slightly different design parameters. This means that sets of comparable implementations are easily obtained by using a sketched design and development approach. Mainly the research only addresses the main demands of feasibility and adequacy. In addition, the complexity of the domains, as is clear from the state of the art described in the chapter, shows that humanitarian demining is open to many possible approaches; Lean viability and technological suitability are relevant constraints, offering valuable novelty, at least from the methodological point of view.

3. Agricultural technology for demining

The study on the landmine issue in developing countries allows identifying a number of aspects that should be considered as characterisation lines. In the current context humanitarian demining is financed and directed by International Organisations in most of the war-affected developing countries. This should deal with the ongoing terrorist activities to get a guarantee on no future deployments of mines in the area would occur in the area. Otherwise, demining activities become a ceaseless operation.

The idea behind the prospected approach is to change the landmine spreading into a basically useless intervention, so that, out of the existing socio-political implications in war-affected countries, no real advantage could be win by terrorist actions; on the contrary, the economical falls-off would be neutral, without serious outcomes into internally displaced people (IDPs), to lower the expected indirect benefits, while leaving open the responsibility hatefulness.

The idea behind the prospective approach is to transform laying landmine into a basically useless activity. Then no real advantage could be gained by the terrorist by laying landmines. And also economic falls-off would be neutral and no serious problem occurred to internally displaced persons (IDPs).

On the outlined objectives, the engineering approach to the mine-clearing business reduces to devising the instrumental process and work organisation to be enabled as routine counter-measure, each time it happens crucial. The operators are enrolled on place. The technologies exploit local know-how, with resort to standard agricultural equipment. The effectiveness assures properly high achievements. The process safety and reliability are consistent with the required duties. Should these figures be reached, the IDPs effects disappear, and the land-mine terrorist spreading ceases to be winning operation, during the tactical occupation of enemy lands, as the routine counter-measure avoids any injuring upshots?

The challenge proposed by the outlined objective is worth the present investigation. In fact, as above recalled, the industrial revolution has science and technology as pivotal aids, but work organisation as critical enabler. The every word ‘industry’ has the original meaning ‘diligence, assiduous activity at any work’, only later modified into: ‘the aggregate of manufacturing production enterprises in a field of business activity, for example, the automotive industry’ or ‘structured organisation, or systematic work or labour’. This leads to acknowledge in the ‘trend to industrial innovation’, the role of the ideas behind technologies, say, chiefly, the ability to pre-arranged assiduous labour (or, *scientific work* organisation) that assures the economic growth, with return on investment because of the diligence of the front-end operators (not on the mastery of individual craftsman or scientist).

Today, of course, we recognise several ‘industry’ levels, replacing the men, with robots, managed by *intelligent work* organisation of self-governing facilities, each time the business awards yield from the (large) fixed assets. Nonetheless, the might of the industrial revolution lies in the aptitude of ruling the workforce totality, by pre-assigned job allocation, once the surrounding outfits are properly chosen, and the pertinent know-how is duly widespread and accepted. Only in such situation, the technologies reach actual appropriateness, and lead to higher income for the involved populations. The following key points have identified as the main objectives when designing any demining machine.

- The engaged technologies shall provide special purpose outfits, having duty-driven consistency and operators adapted uniformity;
- The workflow pre-setting ought to detail the workcycles and standard achievements, and to specify the ongoing failure protection rules;
- The operators' instruction and training aim at off-process optimised workflows, especially, to avoid the emergency of risky engagements;
- The effectiveness comes from organised routine jobs, fulfilled by the workforce diligent activity, in conformity to the allotted tasks;
- The local Civil Service is entitled of the authority to promote the mine-clearing duty, and the involved community is solidly concerned.

Basically, the description assumes the commitment of the neighbouring political societies, to face the terrorist damages, automatically reacting as soon as the raids are undertaken, and immediately putting in action the recovery processes, with resort to the forecast outfits and the pre-arranged schedules. The legal frame does not require any updating, unless the usual elements of the solidarity. The technical support needs to develop according to the ideas of the (original) industrial organisation, with primary focus on the effectiveness of the job-allocation procedures, taken in parallel with the diligence of the engaged workforce.

The proposed approach is consistent with the short-term issues. The counter-measures worthiness is given by the mine-clearing effectiveness, and the present investigation tries to devise how the goal can be achieved according to factual developments. Should the short-term issues be reached, also the long-term ones reconsidered under different light, leading, perhaps, to worthy settlements, with nice economical falls-off, up to the rehabilitation and development of the war-affected countries? Summing up, the approach aims at taking profit from the below statements:

- The resort to Civil Services, managed by the local communities, assures awareness of the remediation duties and consciousness of solidly organised association;
- The effectiveness of standard workflow clearing factually neutralises terrorist landmine scattering, as soon as the socio-economical falls-off mostly evaporate;
- The off-process job allocation and special-purpose outfits development make easy to achieve proper industrial-like productivity, for the community return;
- The processing set-ups can be devised with full technological appropriateness and shared know-how consistency, directly involving pooled competencies.

The advantages/drawbacks balance of the prospected approach depends on how far these statements are met. The present investigation aimed at assessing the feasibility of the last one, which come up to straight engineering commitment and, moreover, needs to be solved as preliminary step, before to address any other statements.

The robot-aided minesweeping (RAMS) project, actually, developed at different ranges, privileges:

- cheapness, to interpret robotics as intelligent work organisation opportunity;
- co-cooperativeness, to involve *in situ* operators, fully trusting their commitment;
- feasibleness, to make resort to locally widespread know-how and apparatuses;
- methodologies, to develop effective minesweeping, with local appropriateness;
- technologies, to assure safe and reliable economic consistency and effectiveness.

The 'robot' solution is needed on the twofold requirement safety/efficiency. The safety is achieved removing front-end operators, directly exposed to the mine bursts. The efficiency is obtained with resort to managing strategic/tactical/execution flexibility with the integrated decision keeping aid of the mixed-mode automation. The proposed and developed RAMS solution is shown in **Figure 3**.

This way the 'robot' are but enabling philosophy, not requiring to develop advanced contrivances, rather to exploit existing apparatuses (mostly obtained from current agricultural equipment), and to integrate them into self-sufficient demining rigs, composed by mobile carriers, with suited effectors, and remote command/steering devices, and into the proper operation methodologies, purposely developed to grant effective minesweeping.

3.1. Operational techniques for demining robots

The RAMS operation management can be divided into three basic functions, planning, development and operation. Planning provides the mode of operation to accomplish the demining operator's goals. Once detailed the demining resources and the management policies, the operation

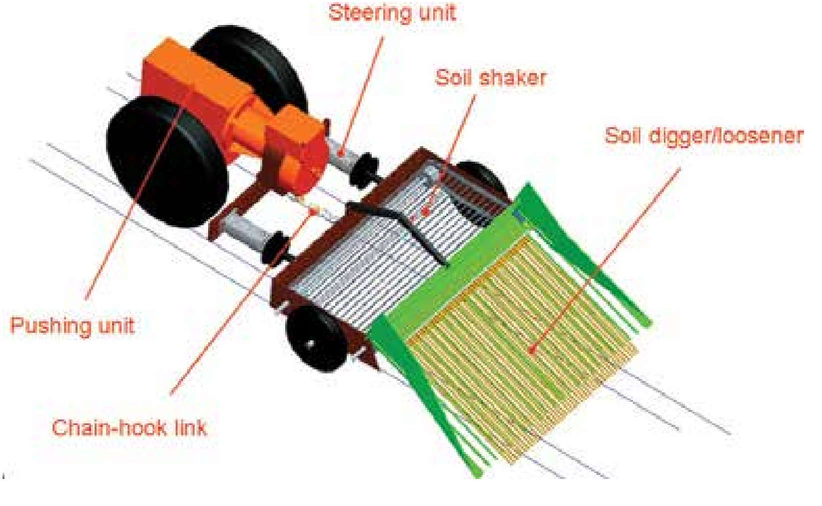

Figure 3. Prospected solution.

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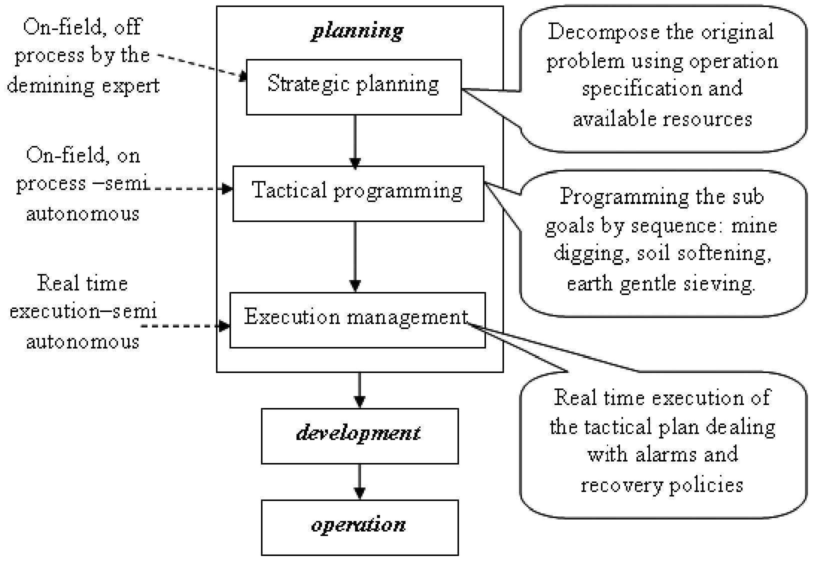

Figure 4. The project-management cycle.

planning is obtained with resort to the usual 'intelligent organisation' paradigms [36], distinguishing the three flexibility horizons: strategic, tactical and execution (**Figure 4**) [37–39]

The development has two levels hardware pre-setting and software pre-setting. The hardware pre-setting is to establish the correct actuators and sensors configurations, while the software pre-setting is to organise the governing and alarm rules. The on-duty operation deals with the overall command architecture, and correspond to the real-time control under supervision of the operator. The strategic horizon deals with the off-process versatility [40, 41], and, for example purpose, the investigation aims at maximising the process effectiveness in keeping with the series of the mobility providers and front-end effectors, actually, implemented; the programmes take into consideration the remote control accomplished by the on-the-field operator, which has the direct visibility of the remote-governed robot, with the connected instrumental data (course, speed, thrust, etc.); the tactical horizon deals with the on-process adaptivity, and, for example purpose, the mine-clearing tasks, done by the power-tiller endowed by the ground stripe lifting, are detailed by the high level 'macro' help, implementing the competing agendas; the pertinent decision aids are developed, with the issues brought to the attention of the operator, which might switch between the agendas, and, eventually, re-initialise the all duty-sequence, driven by the acknowledged 'warning' [42].

The execution horizon deals with the on-duty warnings and the unexpected occurrences [43] (equipment failure, mine deflagration, course stop dead, etc.), and, for example purpose, the above outlined software/hardware setting is acknowledged on multiple-level 'alarm' schedules, depending on the relative risk and frequency, every time detailing the restoring/healing requirements; the occurrence-driven recovery stops the ongoing tactical agenda, and requires the operator consent for the subsequent steps.

4. Conclusion

The humanitarian demining is urgent calamity in the developing countries, not easily faced by the traditional non-profit organisations, when they limit offering spot relief, without transferring to the suffering populations the real proficiency to become self-solvers.

The chapter provides the detailed comparison between different robotic solutions and the overview of a project established in the different spirit, of working out solutions through bottom-up involvement. The 'robotics', we have been dealing with all the study along, is quite awkward. The problem is to exploit the spirit of the technologies, because they are suited to offer solutions. Still the focus is on the «problems», only quite to a limited extent, on the 'technologies'. Once the firmer ones are acknowledged, the way, to find out effective answers, is in sight, on condition that the committed operators accept to become their destiny rulers.

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Section 2

Sensing the Landmines

Chapter 2

UAV for Landmine Detection Using SDR-Based GPR Technology

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Julian David Colorado Montaño and
Iván Mondragón

Additional information is available at the end of the chapter

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Abstract

This chapter presents an approach for explosive-landmine detection on-board an autonomous aerial drone. The chapter describes the design, implementation and integration of a ground penetrating radar (GPR) using a software defined radio (SDR) platform into the aerial drone. The chapter's goal is first to tackle in detail the development of a custom-designed lightweight GPR by approaching interplay between hardware and software radio on an SDR platform. The SDR-based GPR system results on a much lighter sensing device compared against the conventional GPR systems found in the literature and with the capability of re-configuration in real-time for different landmines and terrains, with the capability of detecting landmines under terrains with different dielectric characteristics. Secondly, the chapter introduce the integration of the SDR-based GPR into an autonomous drone by describing the mechanical integration, communication system, the graphical user interface (GUI) together with the landmine detection and geo-mapping. This chapter approach completely the hardware and software implementation topics of the on-board GPR system given first a comprehensive background of the software-defined radar technology and second presenting the main features of the Tx and Rx modules. Additional details are presented related with the mechanical and functional integration of the GPR into the UAV system.

Keywords: ground-penetrating radar (GPR), aerial landmine detection, drone flight control

1. Introduction

Ground-penetrating radar (GPR) is currently a well-accepted geophysical technique which has been successfully deployed with the aim of addressing important sensing problems that requires detection, imaging and identification of dielectric material discontinuities in the subsurface through the use of radio waves, providing a non-invasive method *to probe* the ground. With the existence of different subsurface scenarios with diverse lossy dielectric materials combined with the broad radio frequency, spectrum leads to a wide range of GPR applications. Among these applications, the potential of GPR systems can be extended to landmine detection, considering its intrinsic capacity of detecting electric conductor objects buried into the subsurface.

Nowadays, there are several types of GPR commercially offered. However, within the wide range, two kinds of GPR systems can be identified upon the manner in which the data is acquired, either in *time domain* or in *frequency domain*. Most of commercial GPR systems in use today employ time domain methods and fixed RF electronics to implement impulse-based radar techniques [1–5] where a time domain pulse is transmitted and the reflected energy is analysed as a function of time. The resulting waveform indicates the amplitude of the backscattered energy from the subsurface structures versus time where range information from objects within the subsurface is based on the time-of-flight principle. In terms of size and weight, the main drawbacks of commercial impulse GPR systems are their high price, oversize, overweight and the low adaptability of the system according to the needs of detecting different sizes, types of landmine building materials, and different dielectric characteristics of the terrain due to a fixed-hardware implementation. The limitations of oversize and overweight restrict the fact that the GPR could be installed on-board an unmanned aerial vehicle (UAV) system.

The topics presented in this chapter explore the potential of the software-defined radio (SDR) technology to provide flexible, cost-effective and low-weight radar prototypes for GPR application in the detection of metallic buried landmines. Landmine detection and clearance are one of the primary humanitarian necessities mostly in developing countries with internal war conflicts, for instance, Colombia, which is currently one of the most mine-affected countries in the world. Since 1990, the Colombian government has registered 10,751 victims of explosive landmines: 39% corresponding to civilians and 61% to the military. Although the internal conflict in Colombia is coming to an end, there still are many regions in the country with over 10,000 potentially hazardous areas that require urgent mine clearance, according to recent Colombian government statistics. Besides, most of the landmines in those countries are improvised explosive devices (IEDs) which impose the requirement of the prior knowledge of the target features in order to discriminate between the target and safe objects. IED detection is a challenge due to similarity between IEDs and common objects such as PVC pipes, cans and other objects that are used in the explosive device fabrication. Therefore, the use of SDR in GPR systems can significantly contribute to the identification of IEDs due to its intrinsic capacity of software adaptability.

This book chapter presents an approach for detecting buried landmines by using an autonomous drone equipped with a custom-designed SDR-based GPR system. **Figure 1** details the proposed

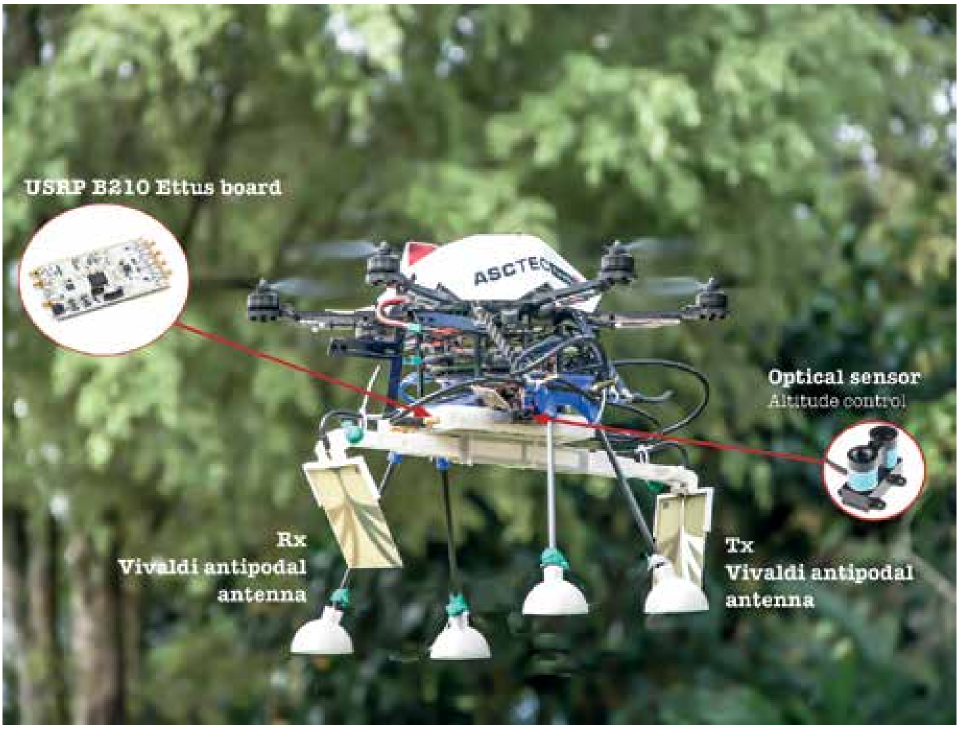

Figure 1. Asc Tec Firefly drone equipped with the custom-designed ground-penetrating radar using SDR methodology.

robotic setup, mainly composed by (i) the GPR system (USRP B210 board, RX and TX antennas and SMA connectors) and (ii) the drone's on-board hardware (high-level and low-level processors, ZigBee communication module, IMU, GPS and LIDAR sensors). One key aspect to achieve a reliable GPR's operation relies on the precise navigation of the drone, which must flight steady in spite of wind disturbances. In addition, the drone must flight at a very low altitude to allow the GPR's emitted signals to properly radiate the subsurface (about 50 *cm* over the ground). Consequently, the navigation controller must take into account the ground effect.

2. Comprehensive literature review

2.1. What are SDR and GPR technologies?

2.1.1. Software-defined radio (SDR)

The origin of the software-defined radio technology is related with the military field, specifically to the Defence Department of the United States with the Integrated Communications, Navigation, and Identification and Avionics (ICNIA) system in the 1970s. Later on in the 1990s, the SpeakEasy project started with the purpose of developing a software programmable radio systems operating in the band between 2 MHz and 2 GHz [6]. This project can be considered as the base of the SDR technology.

In the mid-1990s, Joseph Mitola creates the SDR forum given a detailed description of the technology defining SDR from the engineering design, topological structure and computational structure perspectives [7]. In summary, SDR can be understood as a reconfigurable radio system which substitutes the hardware components such as mixers, filters and modulators into software components by using computing embedded systems. The basic SDR systems are composed by an embedded system with a field programmable gate array (FPGA) interface with a digital-to-analog and analog-to-digital conversion (DAC and ADC, respectively) both adapted to a radio frequency trans-receiver system [8, 9].

2.1.2. Ground-penetrating radar (GPR)

GPR, being the acronym of *ground-penetrating radar*, is a system able to irradiate electromagnetic waves below the earth surface strata and can detect buried objects or differentiate between soil layers by using the principle of reflectometry by dielectric discontinuities of the media [10]. The interaction between electromagnetic waves and the objects located within the radar illuminated area produces the so-called backscattered wave, an echo signal that propagates back towards the surface which can be detected by the GPR receiving antenna for post-processing to obtain underground maps or information of subsurface terrain including the buried objects [11]. The use of radio waves to image the earth was contemplated for decades before some primary results were obtained in the 1950s [12]. From that time, there was a gradual transition of the concepts to sounding soils and rocks in the 1960s and has continued ever since. Nowadays, applications have flourished, leading to a wide research area. A brief historical review is presented in [4, 13]. Some of the current GPR applications are (i) description and characterisation of geological faults, soil stratification, field exploration and mineral resources [14]; (ii) characterisation of materials and structures made of wood, concrete and asphalt; and (iii) detection and identification of buried objects (pipes, cables, barrels, archaeological objects, landmine detection).

Currently, the landmine detection and improvised explosive devices (IEDs) using GPR are the subject of research. The GPR allows detecting both metallic and non-metallic targets in a non-invasive fashion [15]. Unlike metal detectors, GPR technology increases the detection depth range and reduces the false alarm rate. Several GPR technologies and techniques have been addressed in literature oriented to perform a more efficient demining process [16].

There are several types of GPR; the main difference is the way in which data are acquired, either in *time domain* or in *frequency domain*. As an instance, impulse-based radar systems operate in the time domain, while continuous-wave (CW) radar operates in the frequency domain. GPR system can be based on other technologies such as stepped-frequency radar, ultrawide band (UWB), synthetic aperture radar (SAR) and arbitrary wave [17].

2.2. SDR for GPR systems

Since the introduction of the SDR concept, one of the most promising applications that have been taken from is radar. The advantages presented by the SDR technology suits perfectly with the oversize and overweight drawbacks of a traditional radar system [13]. In this manner the term *software-defined radar* has showed up in the picture as a novel paradigm which gives a more versatile solution by implementing the fundamental radar operations such as signal generation, filtering and up-and-down conversion via software [18]. Despite of the synchronisation issues given by the digital nature that the SDR technology can have, undoubtedly the software domain provides advantages such as (i) the possibility to create multipurpose radar, (ii) the possibility to reuse the same hardware, (ii) an easier implementation of advanced signal processing algorithms, and (iii) a faster development and a cost-effective solution. In the last decade, many scientists and researchers are focusing their attention in SDRadar systems and their applications in different test beds considering the Universal Software Radio Peripheral (USRP) as the hardware base and GNU Radio, an open-source software-defined project, as a software tool to implement very sophisticated, cost-effective radar applications.

In the follows, some contributions of SDRadar system are presented. Debatty in [18] presents a compressive state-of-the-art review of the SDRadar technology by approaching from the design concept and global assessment perspectives. In particular, the author mentioned the wide varieties of airborne SDRadar including the one for a UAV to sense and avoid collisions with other flying objects. The work in [19] presents the potentialities of the USRP-based software-defined radars presenting the design and implementation of an SDRadar system for target tracking and the experimental characterisation of the radar on a USRP board obtaining improved radar resolution results with respect to previous works. Other works like the one of Aloi et al. [20] approach in a more detailed fashion presenting the synchronisation issues and practical implementation of a radar system by using Simulink toolbox interface instead of GNU Radio in a USRP device. Recent contributions have shown novel software radar techniques; Costanzo et al. in [21] proposed SDRadar based on orthogonal frequency division multiplexing (OFDM) for soil discontinuity detection taking advantage of the well-known benefits of the multicarrier radar signalling technique employed in various application fields, such as remote sensing of wheatear forecasting, detection of buried objects and interpretation of urban scenes. In the other work presented by the same authors [22], a high-resolution L-band SDRadar is presented for target detection using the USRP NI2920 enhancing the radar bandwidth and range resolution by exploiting the Gigabit Ethernet interface of the SDR system.

2.3. UAV for demining applications

Unlike terrestrial landmine detection mechanisms, the use of unmanned aerial vehicles (UAVs) is clearly suited for covering a minefield without the risk of triggering landmines during the mission. However, the weight and size of the sensing systems used for demining are unlikely to be placed on UAVs due to their poor payload capacity. In [23], the authors proposed the fabrication of a small multi-frequency ground-penetrating radar (GPR) on-board a UAV quadrotor able to lift up to 1.1 *Kg* of payload. The GPR was designed to be a multiband reconfigurable antenna able to switch among a range of radiating frequencies within 0.5–5 *GHz* with a bandwidth of 350 *MHz* to 5 *GHz*. Despite the designed GPR was able to characterise buried landmines with different shapes and depths, the results were conducted in lab experiments with the GPR off-board the UAV, not considering the factors involved in the integration on-board.

So far, biological sensors used by animals (e.g. dogs and rats) provide the highest accuracy in terms of landmine detection. However, to avoid the use of trained animals for demining purposes, authors in [24] have proposed a blimp-based chemosensing UAV with a bio-inspired detection architecture composed by a six-grid array films responding to a wide range of volatile organic compounds. The system creates a map of the terrain with the information provided by the chemosensor. The advantage of this chemosensor technology relies on its small size; however, the sensitivity can go up to few particles per million (ppm), which might not be enough for detecting explosive particles such as Trinitrotoluene (TNT) or Dinitrotoluene (DNT).

In [25], an airborne LIDAR system integrated with laser scanner, GPS and inertial-measurement unit (IMU) is proposed. The system is able to detect TNT and DNT using sensitive biosensors based on the soil bacterium *Pseudomonas putida*. By reflecting a green laser light at a wavelength of 532 *nm* over the explosives, they emit a red fluorescent light. In this regard, multispectral cameras can be used for capturing the traces of fluorescent light. So far, the lightest multispectral cameras commercially available are able to capture visible light wavelengths longer than 520 *nm* and near-infrared wavelengths up to 920 *nm*. They might be an interesting choose for landmine detection.

3. SDR-based GPR design

As detailed in **Figure 1**, the open-hardware platform USRP for developing custom SDR configurations has been used to implement the GPR device. Here, GNU Radio is used, a free and open-source Python programming graphical user interface for software-defined radios to facilitate SDR development. By using the SDR functions contained within the GNU Radio framework, the most fundamental operations of the GPR, such as signal generation, filtering and up/down conversion, are easily implemented via software (unlike the traditional fixed-hardware implementations). Despite the development of SDR has gained a great impact, its full potential has not been fully exploited for radar-based applications applied to landmine detection, concretely, by integrating a GPR into a drone.

The GPR hardware system is composed by two main blocks, the transmitter (TX) and receiver (RX), as shown in **Figure 2(a)**. The Tx module generates the pulse, which is then shaped by a root-raised cosine filter in order to reduce the frequency bandwidth of the signal due to the restrictions of the platform itself. The pulse modulates a carrier that is finally transmitted to the USRP platform to being radiated by the TX antenna. The radiated modulated pulse travels along the path air-soil, and in case of detection, there is a reflected wave, which is sensed by the RX antenna. The RX system down-sampled the signal. The amplitude and delay of the received signal are then post-processed using MATLAB aimed at generating the heat map shown in **Figure 2(b)**. The forthcoming subsections detail on GPR modelling and design.

3.1. Modelling

In order to design and develop the functionalities described, the design considerations described in **Figure 3** have been established. In the first place, the technical specifications of

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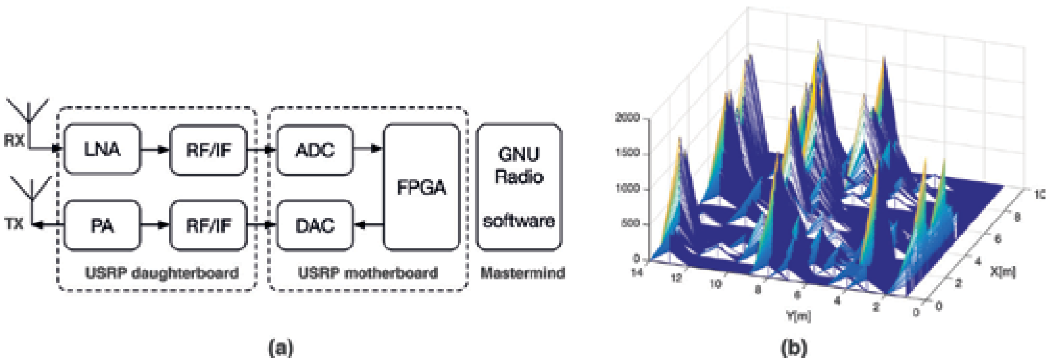

Figure 2. (a) High-level USRP architecture for the GPR implementation; (b) (experimental) post-processed heat map indicating landmines buried in the covered terrain.

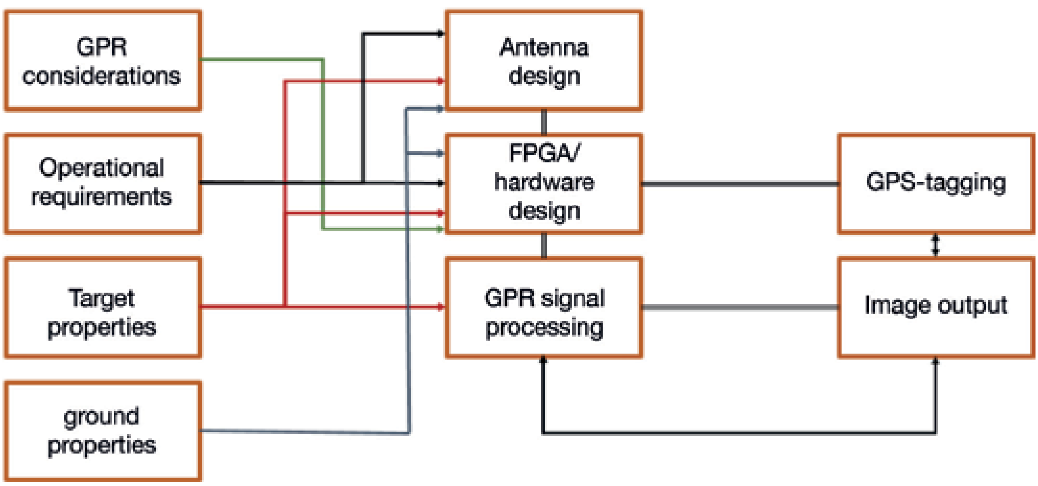

Figure 3. Consideration for GPR designing.

the GPR are defined by taking into account the operational requirements, such as signal frequency operation and bandwidth, propagation speed in different media, noise, etc. Also, it is considered how the aforementioned variables might be affected by the target and material properties. This analysis enables to define and design criteria for developing the antennas, the required hardware and the signal processing algorithms. Finally, GPR storage and visualisation process refer the way how information is stored and presented to the final user.

3.1.1. Geometrical model

A simple geometrical scheme (shown in **Figure 4**) is proposed for setting the inclination angle for both antennas based on analysing reflection and refraction properties that depend on soil materials and target location. This model uses the following geometrical parameters: S is the distance between both antennas, θ_1 is the inclination angle, θ_2 is the signal refraction angle (due to the change of media from air to ground), r_1 is the directional distance between the

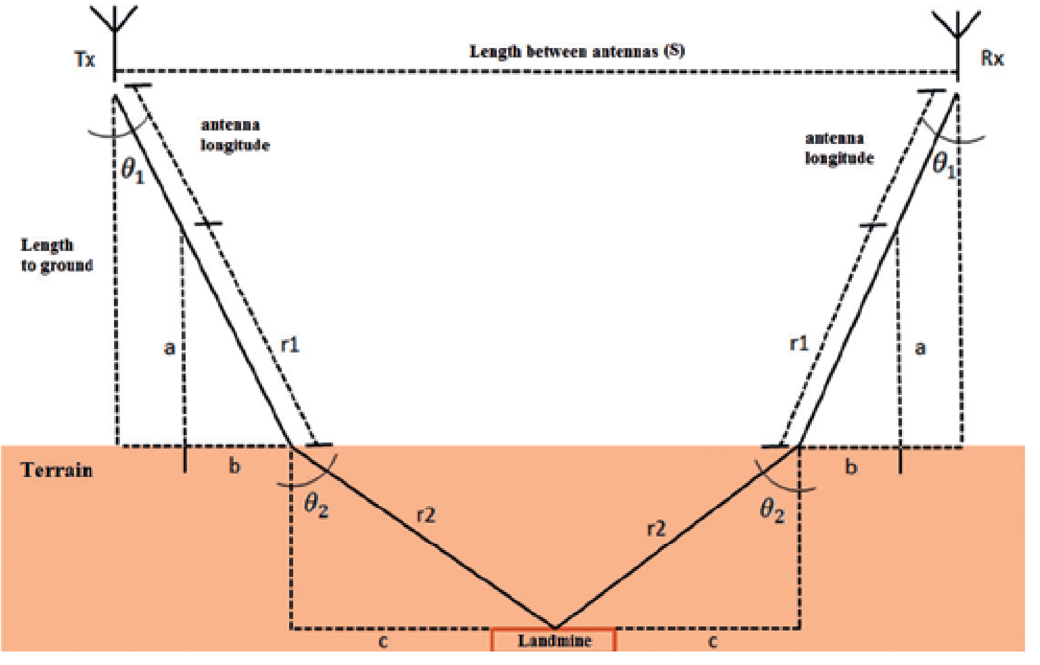

Figure 4. GPR geometrical model for signal transmission and reception.

antenna and the terrain, r_2 is the directional distance to the target (below ground) and a is the antenna altitude with respect to the terrain. By considering the Snell law and applying some trigonometrical properties, the geometrical model is described by Eq. 1:

$$\begin{gathered} \sin(\theta_1) = \sqrt{\varepsilon_2}\sin(\theta_2) \\ a = 0.4 - 0.28\cos(\theta_1) \\ r_1 = \frac{a}{\cos(\theta_1)},\ r_2 = \frac{0.15}{\cos(\theta_2)} \\ S = 2[\sin(\theta_1)(0.28 + r_1) + \sin(\theta_2)r_2] \end{gathered} \tag{1}$$

where the relative air permittivity such as $\boldsymbol{\varepsilon_1} = \mathbf{1}$, the antenna length of **0.28** $\boldsymbol{m}$ and the distance to the terrain **0.4** $\boldsymbol{m}$ are considered. The terrain permittivity ($\boldsymbol{\varepsilon_2}$) can vary drastically, especially in the presence of water particles, and is usually a complex, frequency-dependent quantity with real and imaginary components. For GPR models, it is convenient to simplify the permittivity value to its constant, low-frequency real component with the loss term ignored. This is convenient for the approximate calculation of radar wave velocities, wavelengths and medium impedance; however, it is still too general for a detailed analysis. Relative permittivity of different subsurface materials was taken from [43] and is listed in **Table 1**.

The dielectric material considered for the terrain in the model was a soil (sandy) material considering the limit between dry and low humidity with relative permittivity (ε_2) between 4 and 10. **Table 2** shows the geometrical model data obtained from Eq. (1) for three different incident impinging wave angles.

Material	Static conductivity (σ_s(mS/m))	Relative permittivity (ε_r)
Air	0	1
Clay (dry)	1–100	2–20
Clay (wet)	100–1000	15–40
Limestone (dry)	0.001–0.0000001	4–8
Limestone (wet)	10–100	6–15
Sandstone (dry)	0.001–0.0000001	4–7
Sandstone (wet)	0.01–0.001	5–15
Sand (dry)	0.0001–1	3–6
Sand (wet)	0.1–10	10–30
Soil (sandy, dry)	0.1–100	4–6
Soil (sandy, wet)	10–100	15–30
Soil (loamy, dry)	0.1–1	4–6
Soil(loamy, wet)	10–100	10–20
Soil (clayey, dry)	0.1–100	4–6
Soil (clayey, wet)	10–1000	10–15

Table 1. Typical values of relative permittivity and static conductivity for common subsurface materials at 100 MHz [43].

$\theta_1 = 35°$	$\theta_1 = 45°$	$\theta_1 = 50°$
$10 < \theta_2 < 16,66$	$12,92 < \theta_2 < 20,7$	$14,02 < \theta_2 < 22,5$
$a = 0,118\ m$	$a = 0,129\ m$	$a = 0,135\ m$
$r_1 = 0,144\ m$	$r_1 = 0,182\ m$	$r_1 = 0,211\ m$
$0,152\ m < r_2 < 0,156\ m$	$0,153\ m < r_2 < 0,16\ m$	$0,15\ m < r_2 < 0,162\ m$
$0,3327\ m < S < 0,369\ m$	$0,467\ m < S < 0,511\ m$	$0,551\ m < S < 0,6\ m$

Table 2. GPR geometrical model of **Figure 4**.

3.1.2. Signal power loss model

Power losses are a common phenomenon that must be involved in the development of a GPR system because as described in **Figure 5** the signal faces different changes of medium not only from the air to the subsoil but also within the soil itself. Other signal phenomena should be considered as well like multi-trajectories by reflections of the same signal on the different media surrounding the measurement area. It is also necessary to take into account the distance and alignment between the transmitting and receiving antennas and the backscattered signals.

According to [17], the range of the *GPR* is primarily governed by the total path loss, and the three mainly contributions are the material loss, the spreading loss and the target reflection loss. It should be noted that the considered path loss model, for the sake of simplicity, contains many simplifying assumptions, mainly relating to the spreading loss. In conventional

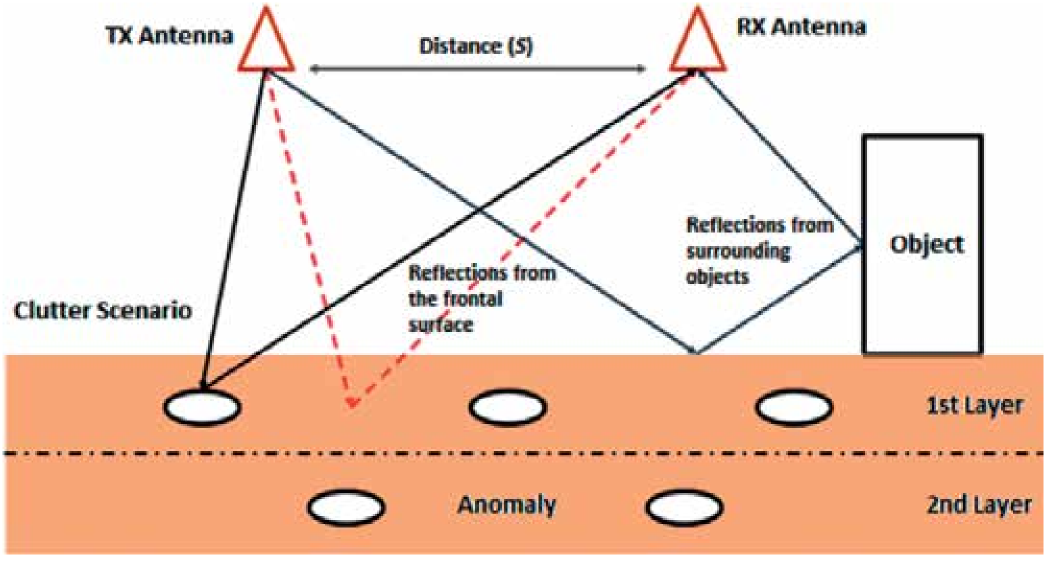

Figure 5. Backscattered signal phenomenon in a GPR scenario.

free-space radar, the target is in the far-field zone of the radiating antenna, and the spreading loss is proportional to the inverse of the fourth power of distance provided that the target is a point source. In many situations relating with ground-penetrating radar, the target is in the near-field zone making the relationship no longer valid. However, for this model, R^{-4} spreading factor is assumed. To model this issue, there were eight factors considered that are related to signal power loss. Then, the overall loss L_T can be modelled as

$$L_T = L_e + L_m + L_{vd} + L_{t1} + L_{t2} + L_s + L_a + L_{sc} \tag{2}$$

where L_e is the loss due to the antenna's efficiency, and considering both transmitting and receiving antennas, the total efficiency loss in the path loss model is $L_e = -4\ dB$. Antenna's efficiency losses were estimated for a loaded dipole antenna; however, for directive antennas, the efficiency is higher and lower losses can be expected. L_m is the antenna mismatch loss, and due to the good match of the antenna shown in lab measurements, it was considered in the order of $L_m = 1\ dB$. L_{vd} is the loss due to antenna's vibrations caused by the drone, L_{t1} is the loss due to the change of the propagation medium (from air to ground), L_{t2} is the loss due to the propagation from ground to air, L_s is the antenna spreading loss, L_a is the loss due to signal attenuation and L_{sc} is the target scattering loss. L_{t1} and L_{t2} can be calculated considering the power transmission loss coefficient defined as $\tau = 1 - |\Gamma|^2$, where Γ is the reflection coefficient which can be computed knowing the air and soil impedance Z_a and Z_m, respectively. Assuming a normal impinging wave, Γ is defined as

$$\Gamma = \frac{Z_m - Z_a}{Z_m + Z_a} \tag{3}$$

By replacing Eq. (3) into the power transmission loss coefficient and computing the power loss in dB, the expression for the transmission coupling loss can be defined as

$$L_{t1} = -20\log\left(\frac{4\,Z_m\,Z_a}{|Z_m + Z_a|^2}\right)\ [dB] \tag{4}$$

Being Z_a = 377 Ω and Z_m obtained by the expression in (7), giving that the subsurface material is mostly soil (sandy) and considering an average dry-wet condition, so the relative permittivity for the terrain was assumed as ε_2 = 8 and the loss tangent was computed by the known expression $tan(\delta) = \sigma/(\omega\epsilon)$ considering a conductivity given by σ = 10 mS/m:

$$Z_m = \left(\sqrt{\frac{\mu_o\mu_r}{\epsilon_o\epsilon_r}}\right)\frac{1}{1 + tan^2(\delta)^{1/4}}\ \left(\cos\left(\frac{\delta}{2}\right) + sen\left(\frac{\delta}{2}\right)\right) \tag{5}$$

Obtaining a terrain impedance Z_m = 130 + j15 Ω, by considering only the real component of the impedance, the air-ground transmission coupling loss is $L_{t1} \approx 2.5\,dB$. Giving the reflection coefficient of the ground-air discontinuity this time as $\Gamma = (Z_a - Z_m)/(Z_m + Z_a)$, Eq. (4) can be also used to find the ground-air transmission coupling loss, so $L_{t2} = L_{t1} = 2.5\ dB$. On the other hand, the antenna spreading loss (L_s) is directly related to the distance between the antenna and the terrain (R) and can be written as

$$L_s = 10\log\left(\frac{G_t\ A_r\ \sigma}{(4\pi R^2)^2}\right) \tag{6}$$

where G_T is the antenna gain, A_r is a known parameter that describes the antenna's effective aperture and σ is the target radar cross section.

Dispersion is the phenomenon that occurs to the signal from the transmitter to the receptor due to non-homogeneities of the medium, especially within the soil that can be modelled as a stratified medium as shown in **Figure 5** turning the wave propagation very dispersive. The losses due to propagation dispersion can be estimated as

$$L_{sc} = 20\log\left(1 - \left|\frac{Z_1 - Z_2}{Z_1 + Z_2}\right|\right) + 20\log(\sigma) \tag{7}$$

The terms Z_1 and Z_2 correspond to the first and second layer impedance of the subsurface material, respectively, and σ is the transversal area of the target. Finally, power signal attenuation due conductivity losses of the different terrain materials can be estimated as

$$L_a = 8,686 * 2 * R * 2\pi f\ \sqrt{\left(\frac{\mu_0\mu_r\epsilon_o\epsilon_r}{2}\left(\sqrt{1 + tan^2(\delta)}\right)\right) - 1} \tag{8}$$

Table 3 summarises signal attenuation values depending on the terrain materials (that are typically encounter in Colombia) and signal frequency.

3.1.3. Time-delay model

Besides modelling signal loss in Eq. (2), we have also considered the velocity of signal propagation (V_r) and the target penetration depth (d). With a soil-simplified model, considering a nonmagnetic isotropic and homogeneous medium both parameters can be computed as

Material	L_a(@ **100** MHz)	L_a (@ **1** GHz)
Wet clay	$5-300\ dBm^{-1}$	$50-3000\ dBm^{-1}$
Dry sand	$0,01-2\ dBm^{-1}$	$0,1-20\ dBm^{-1}$
Dry concrete	$0,5-2,5\ dBm^{-1}$	$5-25\ dBm^{-1}$
Brick	$0,3-2\ dBm^{-1}$	$3-20\ dBm^{-1}$

Table 3. Signal loss due to attenuation phenomenon caused by different materials found in terrain.

$$V_r = \frac{c}{\sqrt{\epsilon_r}} \left[\frac{m}{s}\right] \quad (9)$$

$$d = V_r \frac{t_d}{2}\ [m] \quad (10)$$

where t_d is the signal's delay time from the transmitting to the receiving antenna and c is the light velocity defined as $c = 3 \times\ 10^8\ ms^{-1}$. Relative dielectric permittivity(ε_r) is defined upon the medium where the electromagnetic wave is propagating. Therefore, there are two possible dielectric materials in the GPR scenario, the propagation in air and into the subsurface material. In the first place, the air relative permittivity is a well-known constant defined as $\varepsilon_r = 1$, and so the wave velocity can be rewritten as $V_r = 30\ cm/ns$, with a wavelength between 300 and 30 cm (100 MHz–1 GHz). In the second place, the soil relative permittivity depends on the materials within the subsurface as, for example, if most of the subsurface materials are made of concrete with $\varepsilon_r = 9$, then the wave velocity can be computed as $V_r = 10\ cm/ns$, with a wavelength between 100 and 10 cm (100 MHz–1 GHz). It is worth to notice that the velocity of propagation strictly depends on the relative permittivity, which means that the signal delay's time can vary from medium to medium. This, of course, represents a challenge from the GPR resolution's point of view.

In terms of depth resolution, some GPR applications measure depth by calculating the time involved between the signal reflection caused by the target and the receptor. However, this implies that the terrain has a clean subsurface (e.g. only ground besides the buried target). Clearly, landmine application demands to consider other types of buried elements. Those signals that are reflected by other elements that are not the target cause the clutter effect. The clutter can be defined as those chaotic signals that are measured at the same time and with similar spectral properties than the signal sample of interest. In order to identify the target among other elements (despite the clutter effect), the emitted signal must have a large bandwidth, and the antennas must have a high gain with significant aperture in the lower emitted frequencies. These features are called *resolution plan*.

In the model proposed both *TX* and *RX* antennas are placed with a common offset and depth point with *respect* to the target. **Figure 6** shows this configuration. By properly setting the distance between the transmitter and the receiver, the received power (P_r) can be defined as

$$P_r = \frac{P_t cos^2(\theta)}{d^4}\ e^{(-2\alpha d\ sec(\theta))} \quad (11)$$

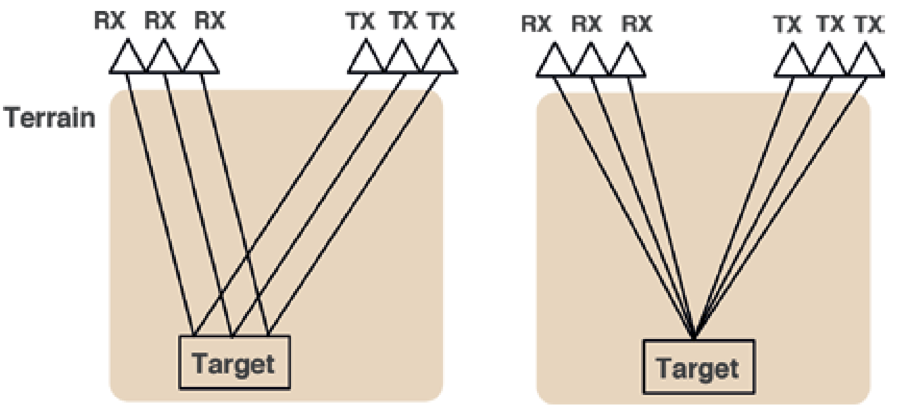

Figure 6. (Left) Common offset; (right) common depth point.

Where α is the attenuation coefficient, θ is the angle of the middle point between both antennas and the vertical distance to the target, P_t is the power of the *TX* antenna and d is the distance to the target. Hence, the *resolution plan* is defined by half of the power measured in those points of signal dispersion (on the surface plane). The resolution can be estimated approximately as

$$\Delta x = 4d\sqrt{\frac{\ln(2)}{2 + \alpha d}} \tag{12}$$

Eq. (12) indicates that the *resolution plan* improves despite the attenuation increases, in which consequence enables the *GPR* system to process a constant signal despite the presence of noise and clutter.

3.2. Hardware

3.2.1. Software-defined radio (SDR) platform

Figure 2 detailed the main components of the proposed GPR system by following an SDR architecture. This section presents a brief description of the hardware components used in the GPR system. The SDR technology has two main hardware components: (i) PC and (ii) A software radio peripheral.

Nowadays, the most representative companies that provide development SDR platforms are Ettus Research (with the Universal Software Radio Peripheral (USRP)), National Instruments (NI-Universal Software Radio Peripheral), Pentek, DataSoft (Thunder SDR), FlexRadio (SDR-1000), Realtek (rtl2832) and lately low-cost SDR platforms as FUNcube Dongle Pro for amateur radio applications. Among the different alternatives, Ettus Research has the largest market segment with a wide variety of SDR platforms with different performances; therefore, the SDR platform used for the GPR application was the USRP B210 from Ettus Research, where the baseband signal processing was performed by the PC on-board the UAV.

The USRP B210 board is divided into two internal boards (**Figure 2(a)**), the *daughterboard* which is in charge of the RF front-end functionalities of the radio system and the *motherboard* that handles all the digital signal processing, such as filtering, shifting and digital up-and-down conversion. Its main function is to deal with the signal's quadrature (Q) and phase (I) components either of the transmitted (digital-to-analog conversion) or received signal (analog-to-digital conversion). As was the case with traditional RF transmitters/receivers (superheterodyne) where the baseband signal was transferred from baseband to an intermediate frequency (IF) and then from the intermediate frequency to the radio frequency, the USRP B210 (*motherboard + daughterboard*) is designed such that the *digital up converter* (DUC) performs the frequency transfer from baseband to IF band frequency and then the *daughterboard* will perform the IF band to RF band frequency transfer. On the other hand, the decimating filters or interpolators in the *motherboard* are used to reach the different binary rates that supports the serial connection (USB or Ethernet) required by the application. As for the clock signal to be used, it can be either external (SMA 1PPS, SMA Ext Ref, SMA GPS) or internal. The clock signal used between the FPGA, ADC, DAC and daughterboard converters was the internal one, in order to optimise the synchronisation of the device. Additionally, the *daughterboard* of the USRP B210 allows operating in *half- or full-duplex* mode with complex signals allowing a fully coherent 2×2 MIMO capability which is used for the pulse transmitting and receiving process in the GPR system

Thus, with the aforementioned information, the USRP B210 board has a frequency cover ranging from 70 *MHz to* 6 *GHz*; it is possible to modulate different signals (via SDR) depending on soil conditions. This makes the implemented system reconfigurable by the user at any time. The modulation process is handled by a FPGA spartan6 chip with a real-time bandwidth of 56 *MHz*. The antennas connected to the *daughterboard* of the USRP were designed by following the Vivaldi antipodal configuration, with a size of 10×8 *cm* and a bandwidth from 1.5 *to* 9 *GHz* with a gain of 7.3 *dBi* at 1.7 *GHz* and 4.3 *dBi* at 2.7 *GHz*.

3.2.2. GPR antenna design

The designed GPR is a time domain system where an impulse is applied to the antenna; there is a requirement for a linear-phase response, and this means that only a limited number of types of antenna can be used. The use of two separated antennas is due to the difficulty found with the use of a single antenna for transmission and reception, which would require an ultra-fast switch to operate in both channels, and since currently it is not possible to obtain commercially available switches to operate in the nanosecond region with sufficiently low levels of isolation between TX and RX ports, most surface-penetrating radar systems use separate antennas for transmission and reception in order to avoid interference from the transmitting antenna at the receiving antenna. Therefore, the cross-coupling level between the TX and RX antenna is a critical parameter in the antenna design for this kind of radars. Typically, a parallel dipole arrangement achieves a mean isolation of -50 *dB*, whereas for a directive antenna arrangement, such levels are higher depending on the antenna's disposal and the directivity of the antenna itself.

On the other hand, the antenna's performance is strictly linked with the terrain material, and in the case of the surface-penetrating radar sensing above the terrain, the antenna will radiate from the air into a half-space lossy material [5]. Some works in literature have reported antenna's behaviour over lossy dielectric materials [26] that summarise the cause modification of the antenna radiation pattern, both spatially and temporally, and should be taken into account in the system design. In addition, the propagation of electromagnetic pulses in a homogeneous conducting earth has been modelled in [27], and the dispersion of a rectangular pulse source suggests that the time domain characteristics of the received pulse could be used as an indication of distance.

In terms of frequency band, a typical antenna used in an impulse radar system would require to operate over a frequency range of a minimum octave and ideally at least a decade, 100 MHz–1 GHz. The input voltage driving function to the terminals of the antenna in an impulse radar is typically a Gaussian pulse, and this requires the impulse response of the antenna to be extremely short in order to not distort the input function generating time side lobes, which can illuminate clutter targets that are close to the target of interest degrading the radar resolution.

In order to have an antenna with a high bandwidth, the Vivaldi antenna was selected for the design. The Vivaldi antennas are part of the tapered slot antenna (TSA) family [28]. This family belongs to the type of longitudinal-wave travelling antenna, i.e. plane antennas whose current and voltage distributions can be represented by one or more travelling waves, which usually travel in the same direction and propagate with a phase velocity less than or equal to the velocity of light [29, 30]. It provides an end-fire radiation and linear polarisation and can be designed to provide a constant gain-frequency performance. TSA are flat antennas that are built on a dielectric substrate. These vary according to the shape of the taper (i.e. the inner profile of the conductive material that goes over the dielectric). There are several kinds of profiles such as linearly tapered slot antenna (LTSA), constant-width tapered slot antenna (CWSA) and exponentially tapered slot antenna (ETSA). The Vivaldi antipodal antenna is characterised mainly by having a broader bandwidth with respect to the return losses of the antenna. Unlike the traditional Vivaldi antenna fed by a conventional microstrip line, the Vivaldi antipodal antenna separates the tapers by placing one on the front face of the dielectric and the other on the back face, as shown in **Figure 7(a)**. In this structure, the feed is made by means of a microstrip line whose ground plane gradually narrows. The proper design of the transmission line ensures that this type of power is balanced and does not need the additional balun. The antipodal configuration guarantees having a wider bandwidth for the matching to the microstrip feed line [35]. Additionally, recent works have shown that the introduction of slots in the antenna taper extends the bandwidth maintaining the good performance of the antenna in terms of radiation pattern and gain [30–33]. Similarly, the use of slots in the taper has been shown to be an effective technique to significantly reduce the size of an antenna without affecting its performance [34, 35], which is ideal for the on-board integration of the GPR with the UAV.

Two Vivaldi miniaturised antipodal antennas for the pulse transmission and reception are integrated to the on-board GPR system, specially designed and fabricated for radar application [36]. As was aforementioned, this configuration is ideal for *GPR* applications. Both *RX*/*TX* antennas are lightweight, with a symmetrical radiation pattern (curves slots), a bandwidth between 1.5 and 9 GHz, a substrate thickness and relative permittivity of 1 mm and 4.6, respectively. **Figure 7(a)** shows the geometrical parameters that directly affect the antenna

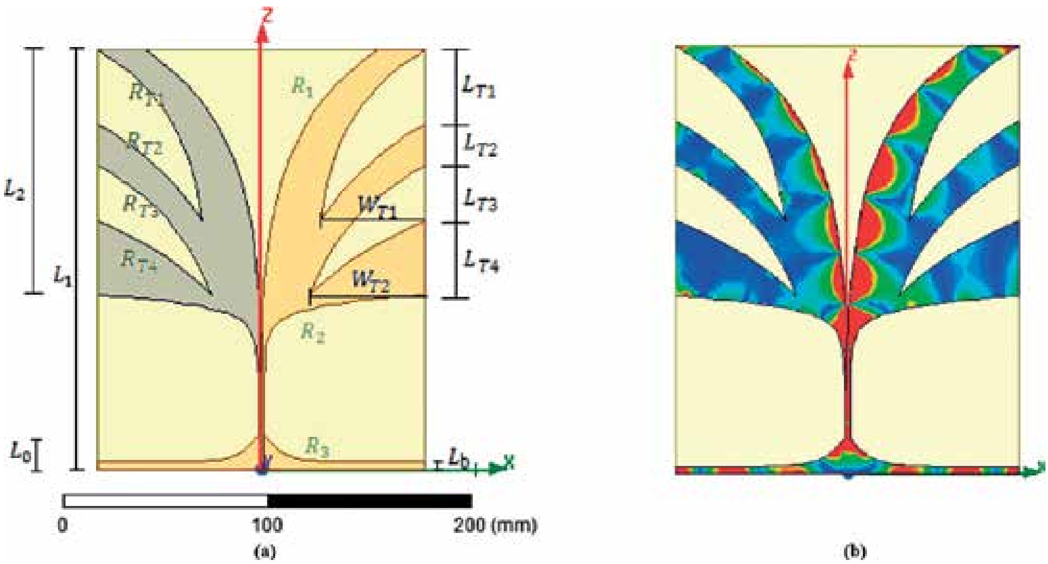

Figure 7. (a) Vivaldi antipodal geometrical antenna parameters. (b) Electric current distribution.

bandwidth. The authors in [36] performed several simulations in Ansoft HFSS aimed at determining the optimised values by means of a parametrical variation experiment. As a result, the geometrical parameters of the fabricated antennas are R_1 = 25 *mm*, R_2 =180 *mm*, R_3 =120 *mm*, L_0 = 17*mm*, L_1 =204 *mm*, L_2 =119 *mm*, = 3.4*mm*, R_{T1} =30 *mm*, R_{T2} = 20 *mm*, R_{T3}=25 *mm*, R_{T4}=25 *mm*, L_{T1}=35.7 *mm*, L_{T2}= 20.4 *mm*, L_{T3} =27.2 *mm*, L_{T4}=35.7 *mm*, W_{T1}=52.36 *mm* and W_{T2}=57.12 *mm*. **Figure 7(a)** shows the electric field distribution on the plane of the antenna. The Tx and RX antenna's radiation patterns are shown in **Figure 8** for different frequencies in the working band showing good agreement between measured and simulated data. Further details regarding the antennas design, simulation and fabrication are found in [36].

3.3. Software

The driver needed to work with the USRP B210 is the USRP Hardware Driver (UHD); it is a library written in C ++ designed to work on Linux, Windows and Mac OS. The main purpose of the driver is to provide control over Ettus products; the use of this software can be used stand-alone or by using other applications such as GNU Radio, LabVIEW, Simulink and OpenBTS. The software implementation of the GPR system can be done under GNU Radio software because it is open and free source and provides a friendly signal processing block interface. Additionally, it is a simulation tool that can be used together with RF hardware (USRP) to physically implement radio software systems.

The GNU Radio project [37] was started in 2001 and was founded by Eric Blossom with the aim of developing a framework for radio software. It consists of a set of files and libraries that provide signal processing blocks, allowing the design and simulation of systems based on radio software. This software tool can be used with additional external hardware such as the USRP, providing the possibility of physically implementing a system based on radio software.

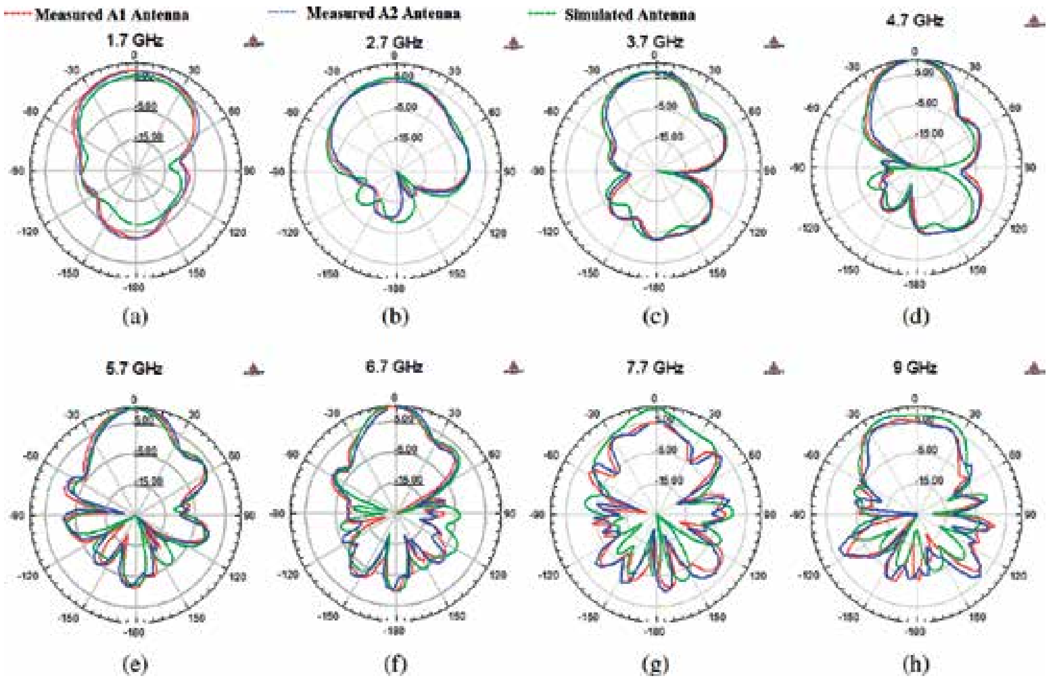

Figure 8. Measured and simulated radiation patterns of TX and RX antennas for the on-board GPR system in different bands: (a) 1.7 GHz, (b) 2.7 GHz, (c) 3.7 GHz, (d) 4.7 GHz, (e) 5.7 GHz, (f) 6.7 GHz, (g) 7.7 GHz, (h) 9 GHz.

The operation of GNU radio can be conceived as a graph, where nodes symbolise signal processing blocks, and the interconnection between them will determine the path that the signal will follow starting from a source and terminating in a sink. Further details of GNU Radio software features, functionalities and applications can be found in its website [37].

GNU Radio applications can typically be programmed in two ways: (i) directly on Python or (ii) using the GNU Radio Companion graphical tool. The second option arises as a need to facilitate the task to the user as much as possible, thus minimising the application programming. The Tx and Rx GPR systems are programmed by using the GNU Radio Companion option, described as follows.

3.3.1. GPR Tx system

The GPR Tx system consists basically in the generation of the transmission impulse. Even though the theory dictates that the signal generated for impulse-based radar must be infinite band, in practical this is not possible because of the technology restrictions of the GPR system's elements. In this case, the generated pulse is band limited since the USRP B210 card has a bandwidth approximately of 56 *MHz*. Therefore, the proposed objective for the designed impulse-based GPR system is to generate a signal with that spectral technology restriction.

The classic rectangular impulse does not cause inter-symbol interference (ISI); however, an infinite bandwidth and significant transmission power are required. For a wireless communication channel, it is necessary to meet the Nyquist ISI criterion, the ISI is generated when consecutive signals are sent through the communication channel and the replicas of the previously sent signals generate interference to the signals that are currently going through the channel which makes the system less robust against noise. To minimise the ISI in a communication channel and concentrate the power within the desired bandwidth, the *pulse shaping* technique is used to shape the impulse according to a specific digital filter; as a consequence, the effective bandwidth and power are concentrated on the main harmonic of the transmitted signal. Not all filters can be used as a *shaping filter* since some of them can actually increase the ISI, so the selection must meet the Nyquist criterion. To this purpose the most common filters are the sinc filter, raised-cosine (RC) filter and the Gaussian filter. Besides, it is important in the reception to include a matched filter according to the transmission filter used. According to this a RC filter was selected because the sync filter is not physically realisable since it is a non-causal filter, and the Gaussian filter is also not viable because it does not have zero crossings and is typically used to generate frequency shifts.

The mathematical function of a RC filter is defined as follows:

$$Z(f) = \left\{ \begin{array}{ll} T_s & 0 \le |f| \le \frac{(1-\beta)}{2T_s} \\ \frac{T_s}{2} * \left(1 + \cos\left[\frac{\pi T_s}{\rho}\left(|f| - \frac{1-\beta}{2T_s}\right)\right]\right) & \frac{1-\beta}{2T_s} \le |f| \le \frac{1+\beta}{2T_s} \\ 0 & |f| > \frac{(1+\beta)}{2T_s} \end{array} \right\} \tag{13}$$

where T_s is the sampling time, β is the roll-off factor which is used to determine the impulse spectrum bandwidth given by Eq. (14):

$$BW = \frac{1+\beta}{2T_s} = \left(\frac{1+\beta}{2}\right) R_s \tag{14}$$

where R_s is the symbol rate. According to the inverse transform of $Z(f)$ of the filter, $z(t) = 0$ for $t = \mp T\_s, \mp 2T\_s$; therefore, for a RC filter, zero crossings are functions of the roll-off factor.

In order to build a RC impulse in GNU Radio companion, first it is necessary to define a square signal and then filter it. However, GNU Radio does not have a square impulse signal generator block; therefore, a well-known method is used, which consists in the multiplication of four square signals with a useful cycle of the 50%, each of them with different frequencies following the rule (f, $2f$, $4f$). With this method it is possible to generate a rectangular pulse train of frequency f and a pulse width $1/4f$ where the pulse width can be made as small as desired, but there are bandwidth limitations. Thus, to generate the transmission signal, the *signal source* block is used with the square waveform option selected, as is shown in **Figure 9**.

With the generated square pulse, it is now necessary to give the form of a RC pulse passing through an elevated cosine root filter which in GNU Radio is known as *root-raised-cosine filter* block. The description of this block is described in **Figure 10**.

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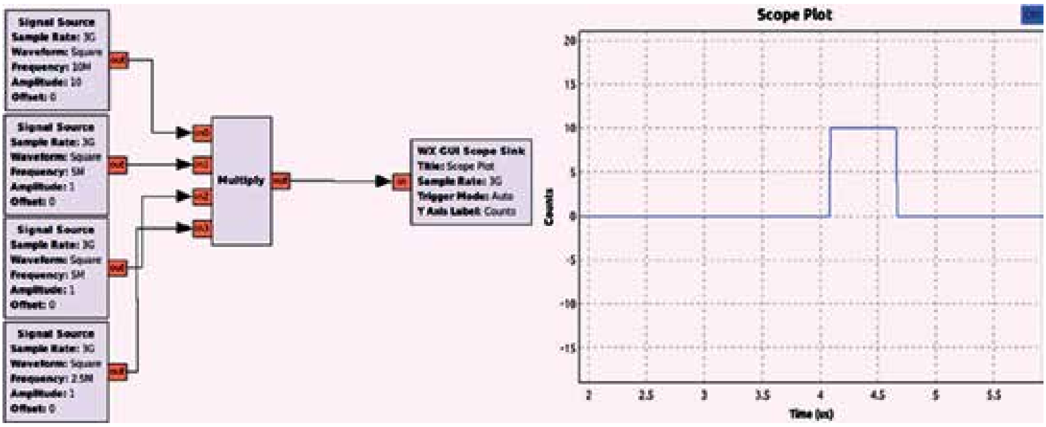

Figure 9. Rectangular pulse train generator in GNU Radio Companion.

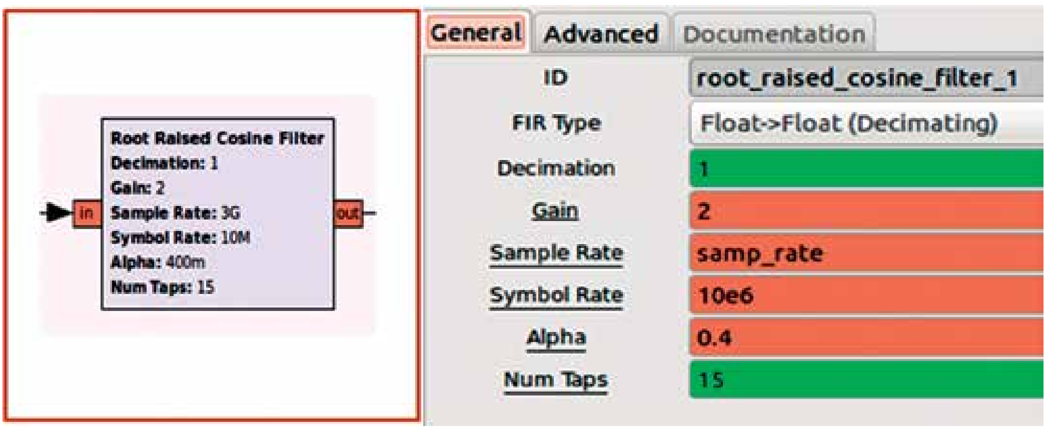

Figure 10. GNU Radio RC filter block parameters.

Within the RC Filter block, it is possible to set the decimation value, filter gain, sampling rate, symbol rate, roll-off factor (alpha) and number of taps for floating and real values according to the criteria of design and operation of the filter. The choice of decimating or interpolating is very important in the filter design, and the two are the equivalent of a down-sampling and up-sampling process, respectively. Both are integer values that allow increasing or decreasing the number of times a sample is replicated in the ADC process. The symbol rate (baud rate or modulation rate) is the number of pulses per unit of time (pulse/second).

The RC filter is a finite impulse response (FIR) filter used for *pulse shaping* which means that its impulse response has a finite duration [39]. This parameter is set by the number of taps, which for this application is 15 by default.

After the generation of the RC pulse, an additional modulation process is considered for further distortion reduction. The final transmission pulse is shown in **Figure 11**.

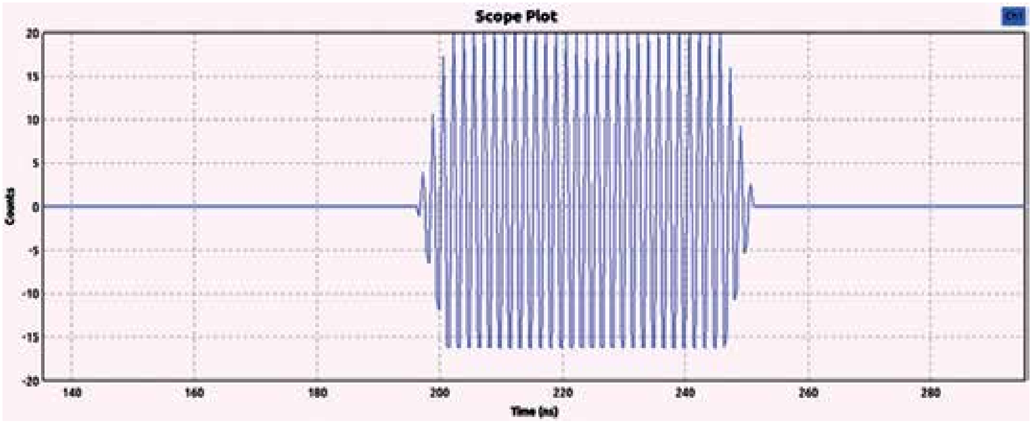

Figure 11. RC transmission pulse.

3.3.2. GPR Rx system

The received signal (Rx) is processed in order to detect a buried landmine. To this purpose, we need to introduce the following procedures: (i) signal filtering, (ii) setting a gain for quantifying the incoming power and (iii) designing the detection algorithm. By using the *USRP source block* provided by GNU Radio, we can set up the gain, the central frequency and the sample rate.

On the other hand, as was mentioned before, the detection algorithm is based on a matched filter that enables to maximise the signal factor despite the noise (high signal-to-noise ratio (SNR)); in other words, it enables to detect the waveform of the signal (emitted pulse) despite the noise. The matched filter is a linear filter normally used in radar systems designed to detect a pulse shapes despite the presence of clutter noise. Once the drone has covered an entire terrain, the data captured by the GPR is post-processed in order to generate a heat map. Hence, Rx signal is of the form

$$v(t) = Ax(t - t_o) + n(t) \tag{15}$$

where (t) is the transmitted pulse, t_0 is an unknown delay and A is a scaling factor. The output of the filter is $v(t) = v(t) * h(t) = y(t) + n_0(t)$, where $h(t)$ is the impulse time response after applying the convolution property $(A + B) * C = A * C + B * C$. Hence

$$y(t) = \left(Ax(t - t_o)\right) * h(t) \tag{16}$$

$$n_o(t) = n(t) * h(t) \tag{17}$$

In time, the term t_d in Eqs. (18) and (19) represents the time when the transmitted pulse is received by the Rx antenna. The expression for the *SNR* can be written as

$$SNR = \frac{|y(t_d)|^2}{|n_o(t)|^2}\ max \tag{18}$$

$$SNR = \frac{\left| \frac{1}{2\pi} \int_{\infty}^{-\infty} X(\omega) H(\omega) e^{j\omega t_d} \, d\omega \right|^2}{\frac{1}{2\pi} \int_{\infty}^{-\infty} S_1(\omega) |H(\omega)|^2 \, d\omega} \tag{19}$$

By applying the inequality Cauchy-Schwartz in Eq. (19), the response of the filter is

$$H(\omega) = \frac{X(\omega)^*}{S_n(\omega)} \, e^{-j\omega t_d} \tag{20}$$

By assuming white noise, S_n (ω) is the constant, and considering the Fourier transformation properties described in Eqs. (21) and (22), the expression for the filter response can be written as in Eq. (23):

$$X^*(\omega) \rightarrow x * (-t) \tag{21}$$

$$Y(\omega) e^{-j\omega t_d} \rightarrow y(t - t_d) \tag{22}$$

$$H(\omega) = X^*(\omega) e^{-j\omega t_d} \rightarrow h(t) = x * (-t + t_d) \tag{23}$$

Based on the above considerations, the filter used as a matched filter is also a RC filter.

In the post-processing stage, the way of indicating a mine presence to the user has two approaches: by audio and by construction of a heat map. The audio recognition method is similar in operation to that of a conventional metal detector which emits an audible signal under the event of a positive mine detection. When a target is located, the received power is greater, and consequently the response's amplitude of the matched filter is also greater; then the signal is processed by a function in GNU Radio to obtain the RMS value of the signal and is sent to a VCO where it fits the audible spectrum so that the sound is differentiable with respect of a non-mine event. The blocks in GNU Radio that describe this function are shown in **Figure 12**.

On the other hand, the method of recognition by construction of a heat map unlike the acoustic method requires further processing of the results. To this purpose, the GPR data are exported with a *file sink* block from GNU Radio for post-processing in MATLAB. Results are shown in Section 4.

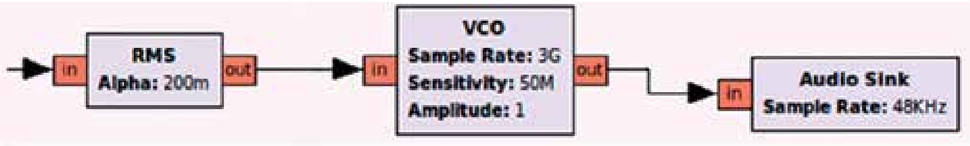

Figure 12. Audio mine indicator system in GNU Radio Companion.

4. SDR-based GPR integration on-board UAV

This section describes the on-board integration process between the GPR system and the UAV. The process includes the integration of hardware, software and the mechanical parts corresponding to the necessary supports for the correct coupling of both systems for a suitable flight plan for the GPR correct function. Being independent devices, the UAV and the GPR need a mechanical supports specially designed to fit with the physical area of the UAV system. In addition, it is also necessary to establish continuous communication between the equipment in such a way that the flight system is in charge of assigning processes, while the GPR system is a peripheral that executes those processes. Finally, the data obtained by the GPR together with the GPS data and positioner values of the board must be correctly archived, so that the base station can extract and post-process them for further analysis.

4.1. Mechanics

The mechanical integration of the radar with the UAV is realised by means of an adjustable, resistant and light support, which allows several antenna positions according to the height of flight and the depth distance of the buried landmines. For the support design, the geometric model (**Figure 4**) is taken into account for the signal transmission and reception. As was mentioned in Section 2.2, the designed GPR system is implemented using the Ettus USRP B210 [38] card from Ettus Research and two antipodal Vivaldi antennas especially designed for radar applications explained in Section 2.2.2. Based on the above, the CAD models were designed for each of the necessary components.

For the SDR support CAD model, the physical dimensions of the SDR card were taken into account and designed in such a way that the card would slide through the support and be adjusted with the SMA connectors at one end. The model is shown in **Figure 13**.

For supporting the antennas and SMA cables, an adjustable rail system is designed in such a way that the separation between the antennas is variable between a minimum distance of 307.66 mm and a maximum distance of 669.69 *mm*. The separation distances were computed from the geometrical model considering that the inclination angle of the TX and RX antennas can vary from $8°$ to $18°$ and the relative terrain permittivity between 4 and 8, approximately. The different configurations allow setting the best receiving signal scenario depending of the landmine depth. One of the arms of the adjustable rail system is shown in **Figure 14**. The complete CAD model of the adjustable rail system is shown in **Figure 15**.

The designed CAD models are fabricated using the 3D object professional printer using a simulated polypropylene material that gives strength and flexibility to the structure. The weight for the total and each piece of the mechanical support are given in **Table 4**. It is worth to notice that the total weight meets the restriction of the UAV payload.

4.2. Communications

The UAV has by default a 64-bit Linux operating system. However, due to compatibility problems, GNU Radio is installed over a bootable USB memory with a 64-bit Ubuntu 14.04

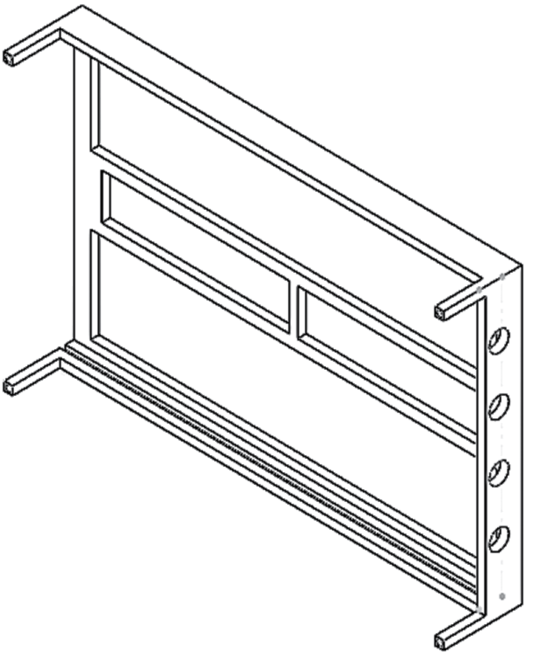

Figure 13. SDR support CAD model: large 15.77 *mm*, width 103 *mm* and height 28 *mm*.

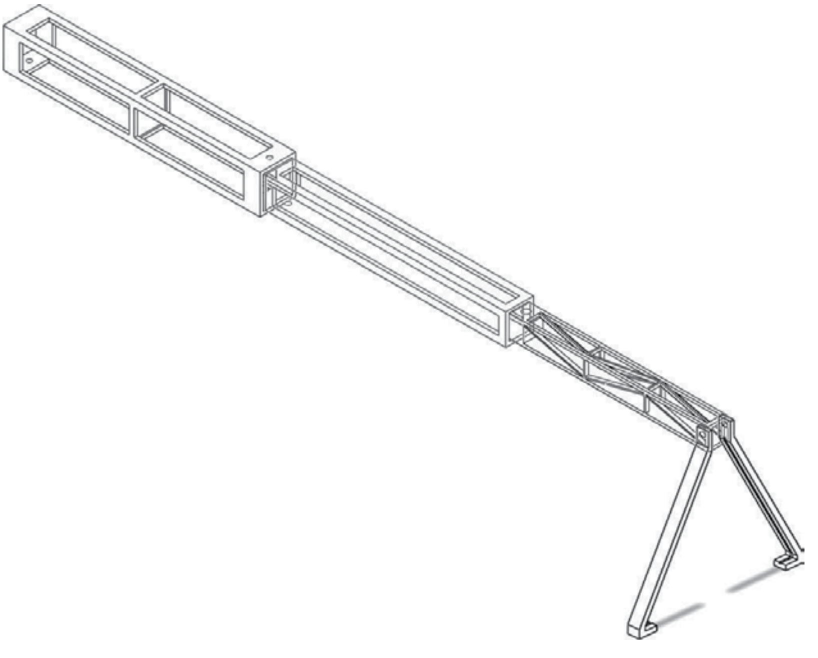

Figure 14. Arm of the adjustable rail system CAD model with the antenna support.

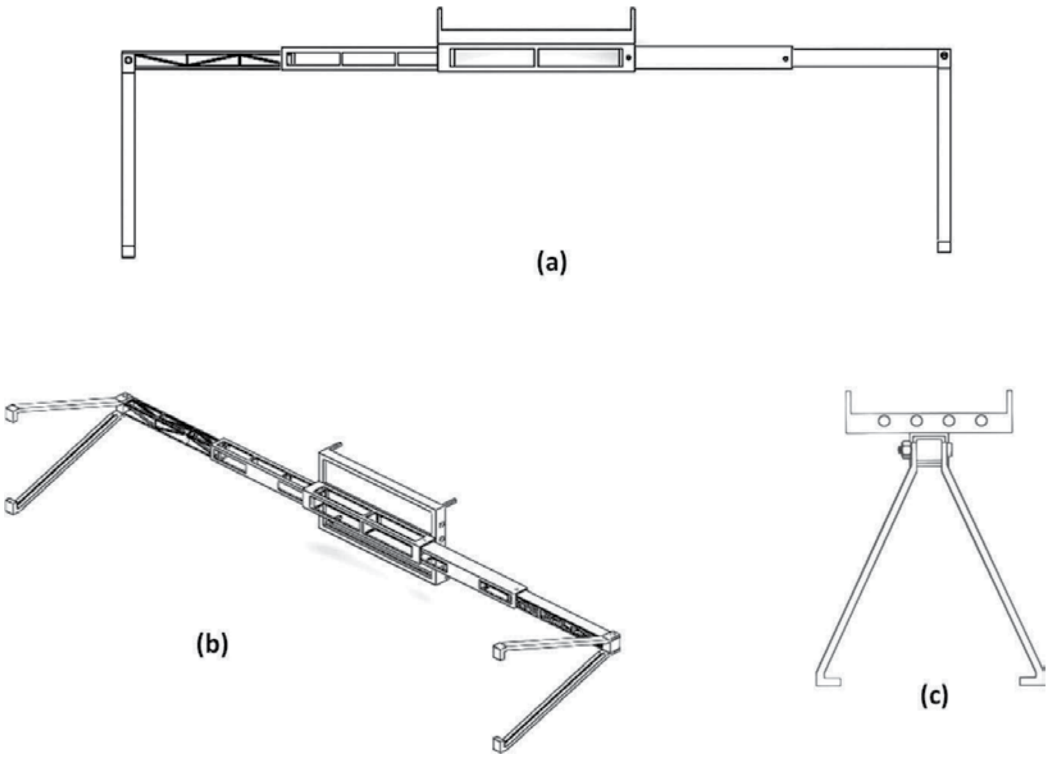

Figure 15. Rail system CAD model: (a) front view, (b) isometric view and (c) lateral view.

Piece	Weight
B210 support	20 g
Rail system with antenna support (×2 arms)	97 g
Landing gear	340.21 g
Antennas (×2)	68 g
USRP B210 SDR	99 g
Cables SMA-SMA (×2)	34 g
Total weight	**658.21 g**

Table 4. Total weight of the overall integrated system.

operating system. In this fashion, the UAV Mastermind instead of starting with the default operating system started with Ubuntu from the USB allowing the operation of the GPR system.

On the other hand, the communication between the computer on-board and the base station is made by means of the SSH protocol since it has strong security protocols and it ensures a stable process execution by keeping processes running on the server until the link is re-established when communication with the client is lost.

4.3. Graphical user interface (GUI)

The GUI enables the user to set up the desired trajectory (waypoint navigation) (**Figure 19(a)**), key parameters of the GPR and other features such as saving a log file of the flight or computing a terrain image mosaic with the sequences of images captured by the drone during flight. This work has been approached in a previous work cited in [40].

4.4. Landmine detection and geo-mapping

The Autopilot card of the UAV is programmed using the so-called variable *wpreached* that allows knowing if the UAV is inside a waypoint. The UAV is programmed using the Eclipse software and the help of the AscTec wiki which contains the entire development package and corresponding codes for the programming of the Autopilot card. The programming of *wpreached* is done in an SDK.c file. Within this file there is an example of waypoint tracking, in which the UAV performs a square of 15 × 15 m. Therefore, a new *wpreached* subroutine was created to guide automatically the UAV through waypoints, including the execution commands of the GPR. The GPR data acquisition is done for each of the defined trajectories by the Autopilot program with the settled waypoints as shown in **Figure 16**.

The data are stored in two self-contained folders in the mastermind's desktop, one with the GPS and one with GPR data. The results of the GPR are stored automatically in GNU Radio in a binary file with different names for each of the trajectories. On the other hand, the GPS and IMU data are stored in a text file which is divided into six columns representing the data of each required value. The renaming and creation of radar and GPS files, respectively, are done

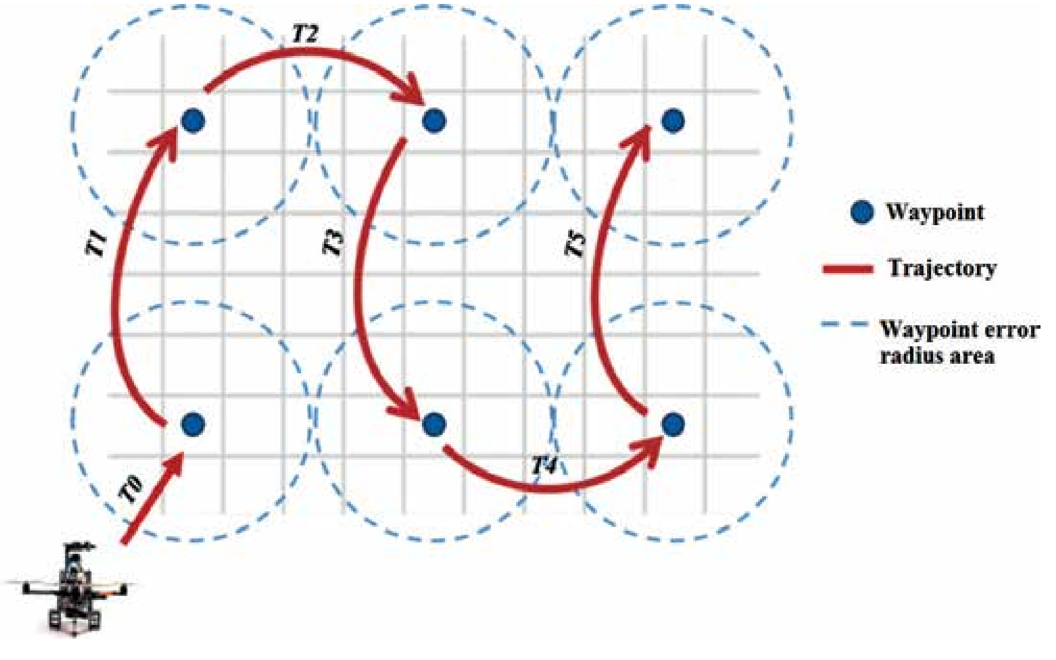

Figure 16. Autopilot trajectory UAV workplan with waypoints.

autonomously without user intervention during the rest of the time of the UAV at the waypoints.

In order to geo-locate the identified landmine targets within an image (geodesical position), the odometry between consecutive images has been computed by using the on-board IMU data of the UAV [41]. Once the landmine is geo-located, a map of the terrain is created by computing an image mosaic. Image mosaicking is a process for building a panoramic image that result from combining multiple photographic images taken with an on-board camera. The geodesic coordinates of the detected landmines are obtained by using the UAV on-board GPS through a robot operating system (ROS) package called *drone_GPS* which enables to transform geodesic coordinates captured by the GPS into Universal Transverse Mercator (UTM) coordinates for positing the robot on earth. Further details of landmine geo-mapping can be found in [40].

5. Results

Recalling the workflow depicted in **Figure 17**, the steps followed in order to perform a mission are as follows: (i) the operator selects the GPS coordinates of the starting point of the mission (via Google Earth). By using the GUI of the ground station, the operator defines the path to cover a desired area. (ii) Before proceeding to real experiments, the operator must start the

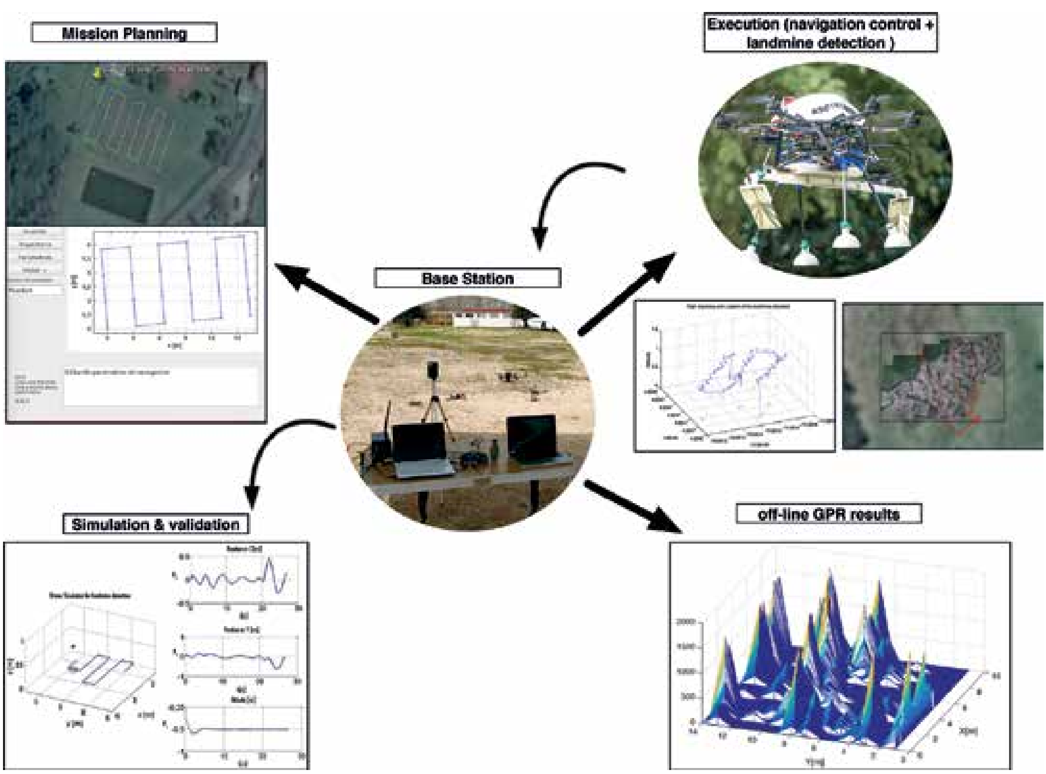

Figure 17. Operation workflow of the UAV with an on-board GPR integrated system.

simulator (requires MATLAB) in order to verify that the drone is able to operate at the desired altitude and speed. (iii) Once the mission is validated, the operator must send the mission parameters to the drone (via clicking *send* in the GUI), including list of trajectory waypoints, commanding height and speed and GPR configuration parameters. (iv) By clicking *start*, the drone waits until the operator takes off manually up to about 1 *m* over the ground. Using the RC controller, the operator switches to autonomous mode. The drone's altitude control positions the drone at about *50 cm* aimed at ensuring proper GPR performance. The autopilot position control uses GPS feedback to track the path waypoints, while a backstepping+DAF attitude control enables steady flight [42]. The operator is able to abort the mission by moving any stick of the RC controller. (v) Once the drone finishes the mission, the drone sends all data to the base station and waits for manual landing. (vi) Within the base station, the operator can visualise GPR results and the geo-mapped terrain. The forthcoming section presents the experimental results for the integrated aerial system for landmine detection.

5.1. Landmine detection results

Experiments with the complete system have been carried out nearby a small rural area. The drone covered a small terrain with an area of 35 m^2, with a flying speed of $0.12ms^{-1}$ and a mission time of 100*s*. In the experiment setup, there are three buried landmine prototypes along the terrain: (#1) bottle-made artefact, (#2) fully metallic artefact and (#3) PBC tube-made artefact. The insets of **Figure 18(a)** depict each prototype. Artefact (#1) is a bottle buried at 20 *cm* in depth with 8 *cm* of diameter and 20 *cm* in length with 20% of non-uniform metal component. It covers an area of 16 m^2. In some countries like in Colombia, most of the landmines are hand-crafted; this is why the enclosures are typically made by such components. In the inside of the bottle lies the explosive, copper cables, battery and tape. Artefact (#2) is a fully metallic buried at 10 *cm* in depth with 25 *cm* of diameter and 10 *cm* in length, and it covers an area of 156 cm^2. Artifact (#3) is a PBC tube buried at 20 *cm* in depth with 16 *cm* of diameter and 10 *cm* in length, and it covers an area of 60 cm^2. In the inside, artefact (#3) has 30% of non-uniform metal component.

In addition, other two types of metallic elements are buried working as false alarms. **Figure 18 (c)** shows how these five elements (three landmines and two false landmines) are spatially distributed along the terrain. Elements #4 and #5 are fully metallic layers with 15 × 15 × 15 *cm* and 20 × 15 ×5 *cm*, respectively, both buried at 15 *cm* in depth and covering an area of 225 cm^2 and 300 cm^2. We divided the entire area within cells in order to map the position of the artefacts detected by our system. Internally, the GPR detection signal looks like the ones depicted in **Figure 18(b)**: in the left, we have a signal with larger amplitude compared to the right one, meaning that a possible landmine has been detected. Finally, **Figure 18(d)** shows the generated heat map with the GPR results. This map condenses the results of 20 different instance measurements carried out over the same surface described in **Figure 18(c)**.

Experiments were conducted with an average ambient temperature of 14°C with an average solar radiation of $4.4kW/m^2$ and a relative humidity of 72%. This means that the soil was always a little bit wet, which consequently makes difficult full penetration of the GPR signal below the surface. To quantify the performance of our system in terms of accuracy and reliability, we have calculated the receiver operating characteristic (ROC) data detailed in **Table 5**.

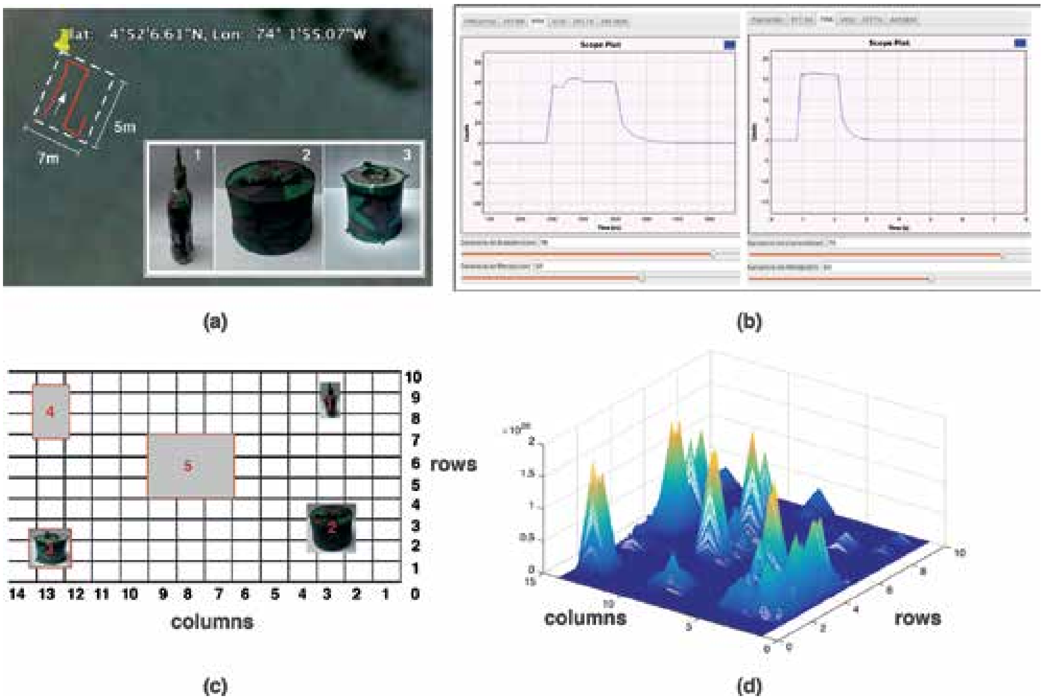

Figure 18. Experimental landmine detection results: (a) the corresponding field for testing the system. The insets show three landmine *artefacts* of different forms, sizes and materials; (b) signal processed by the *GPR* using *SDR* GNU radio: in the left, a signal with large amplitude indicating a buried *artefact*; (c) grid showing the location of each element, including the three landmine *artefacts* and two additional non-landmine elements; (d) heat map computed from the *GPR*/*GPS* data after the experiment. Large peaks correspond to a detected object.

Comparing the results from the heat map in **Figure 18(d)** against the location of the artefacts from **Figure 18(c)**, note that the landmine (#1) (bottle-made artefact) was not properly detected. The corresponding GPR signal for landmine (#1) can be barely observed in the coordinates: **rows 8–9** with **column 3**. As mentioned, the enclosure of this artefact was entirely made of plastic with only 20% of non-uniform metal component in the inside. Other critical issues rely on the small transversal area of the artefact, about 16 cm^2. Recalling the geometrical model defined in **Figure 4**, the angle θ_2 enables to set up the GPR aimed at detecting buried artefacts of larger size and length but with small transversal area, such as the bottle. However, there is a limit in the amount of area and the amount of metal in the material.

It was experimentally found that the limit with the measurements carried out for the artefact (#3): a tube-made artifact with an enclosure made of PBC with 30% of non-uniform metal component in the inside. Comparing Artefact (#3) with (#1), both are buried at the same depth with similar morphology, but the former has a larger diameter; thus, it has a larger area of 64 cm^2. Also, the former has 10% more metal in the inside. The corresponding GPR signal for landmine (#3) was fully detected in the coordinates: rows 1–2 with column 13.

The corresponding GPR signal for landmine (#2) was fully detected in the coordinates: rows 1–5 with columns 2–4. This artefact was fully made of metal with a transversal area of 156 cm^2.

Variable	Value	Description
True positives (TP)	4	Positive artefact indication-artefact in place
True negatives (TN)	2	Negative artefact indicator- artefact not in place
False positives (FP)	0	Positive artefact indicator- artefact not in place
False negatives (FN)	1	Negative artefact indication- artefact in place
True positive rate $\left(TPR = \frac{TP}{TP+FN}\right)$	80%	Correct positive results among all positive samples
False positive rate $\left(FPR = \frac{FP}{FP+TN}\right)$	0%	False alarm
Accuracy $\left(ACC = \frac{TP+TN}{TP+FP+FN+TN}\right)$	85.7%	Reliability of the alarm
Positive predictive value $\left(PPV = \frac{TP}{TP+FP}\right)$	100%	
Negative predictive value $\left(NPV = \frac{TN}{TN+FN}\right)$	66.6%	

Table 5. ROC detection results.

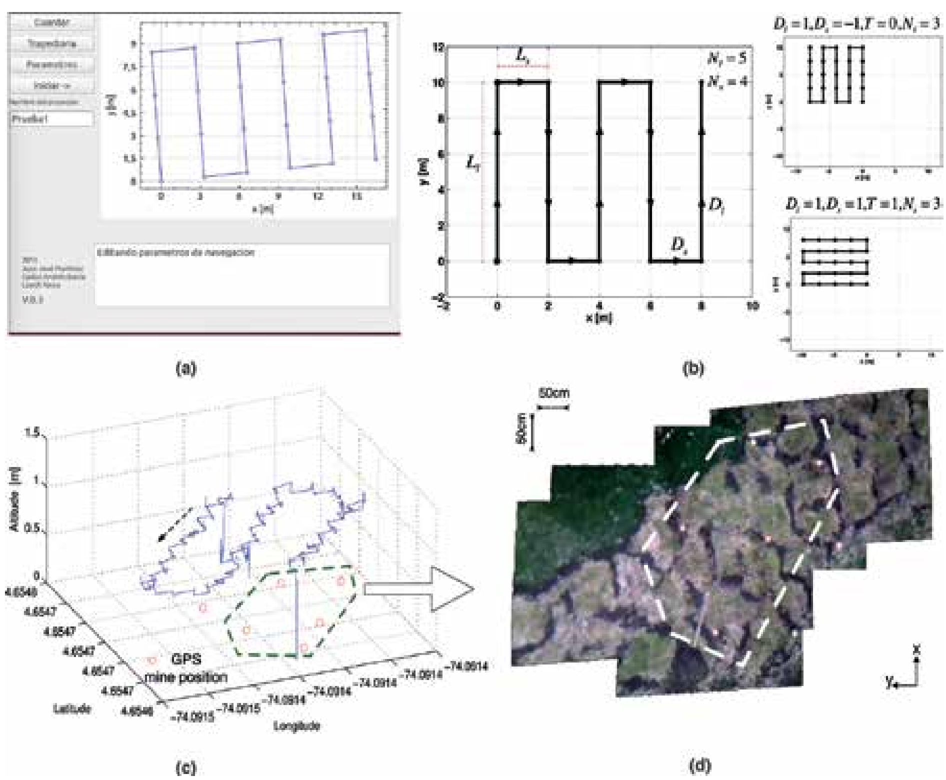

Figure 19. (a) Initial GUI for the setting of the waypoint of the flight plan. (b) Trajectory plan generation and navigation control. (c) Experimental *3D* trajectory of the *UAV*: covered area of 80 m^2 at 2560 m above the sea level. The red circles are *GPS* coordinates of the detected landmine objects. The inset shows how the detected target is displayed to the user via the base station's interface, (d) panoramic image of the covered terrain. The mosaic map was created by applying a stitching method to the images captured by the *quadrotor* during flight.

Finally, elements (#4) and (#5) (metallic layers acting as false landmines) were also detected by our system. In real missions for demining (mine detection and clearence), buried metallic objects that do not correspond to real landmines will be detected as landmines (true negatives). In summary, the designed system under the aforementioned operational characteristics will have an accuracy of 85%, a true positive rate of 80%, a positive predictive value of 100% and a negative predictive value of 66.6%.

5.2. Geo-mapping results

In this subsection, experimental results of the geo-mapping process are presented. In overall, it has been analysed 28,029 images captured by the drone during flight. On average, the drone has covered terrain areas ranging from 15 m^2 to 80 m^2 with a flight altitude ranging from 0.5 m to 1.5 m. **Figure 19(a)** shows the trajectory followed by the drone while covering an area of 80 m^2. The red circles represent the GPS coordinates of the detected landmine objects during flight.

6. Conclusions

This chapter has presented the development of a custom-designed lightweight GPR by approaching interplay between hardware and software radio. Additionally, the chapter introduces the integration of the aforementioned SDR-based GPR into an autonomous aerial drone (UAV). The performance of the GPR from the results obtained validates the possibility to integrate a lightweight radar system into a UAV.

In terms of GPR performance, the directional antennas radiated and received more power in a specific direction, which consequently increased the detection by means of reducing the interference caused by other sources. Also, thanks to the mathematical model derived for the *GPR* system, we were able to design a *SDR*-based *GPR* that can be reconfigured during operation. This introduces the possibility of adjusting the *GPR* (power, frequency, bandwidth, carrier, etc.) depending on the testing scenario. In overall, our proposed system was able to detect buried *artefacts* with smaller transversal areas that do not necessarily need to be made full of metal. The outdoor experiments have enabled us to establish the following conditions and limit for an accurate detection: relative humidity > 70% (semi-wet or dry terrain), *artefact* depth 20 *cm*, and diameter (> 15 *cm*) with a transversal area > 16 cm^2 and > 30% of the material made of metal.

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Section 3

Robots in Nuclear Plants

Chapter 3

Towards Advanced Robotic Manipulations for Nuclear Decommissioning

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Abstract

Despite enormous remote handling requirements, remarkably very few robots are being used by the nuclear industry. Most of the remote handling tasks are still performed manually, using conventional mechanical master-slave devices. The few robotic manipulators deployed are directly tele-operated in rudimentary ways, with almost no autonomy or even a pre-programmed motion. In addition, majority of these robots are under-sensored (i.e. with no proprioception), which prevents them to use for automatic tasks. In this context, primarily this chapter discusses the human operator performance in accomplishing heavy-duty remote handling tasks in hazardous environments such as nuclear decommissioning. Multiple factors are evaluated to analyse the human operators' performance and workload. Also, direct human tele-operation is compared against human-supervised semi-autonomous control exploiting computer vision. Secondarily, a vision-guided solution towards enabling advanced control and automating the under-sensored robots is presented. Maintaining the coherence with real nuclear scenario, the experiments are conducted in the lab environment and results are discussed.

Keywords: nuclear decommissioning, robot tele-operation, robot vision, visual servoing

1. Introduction

Nuclear decommissioning, and the safe disposal of nuclear waste, is a global problem of enormous societal importance. From the world nuclear statistics, there are over 450 nuclear plants operating in the world and out of which, 186 are currently being operated within Europe [1].

At present, nuclear industry forms the main basis for approximately one quarter of the EU's total power generation, which is forecasted to be increase by at least 15% by 2030. Nuclear operations in USA and UK began in the 1940s, and greatly accelerated in both countries following the first USSR atomic bomb test in 1949. UK pioneered peaceful use of atomic energy, with the world's first industrial scale civil nuclear power plant coming online at the UK Sellafield site in 1956. Thus, in several countries, legacy nuclear waste materials and facilities can be more than two-thirds of a century old. Due to the raising concerns over fossil-fuelled power generation especially with the alarming levels of greenhouse gasses and the difficulty in managing nuclear waste, many nuclear plants worldwide are undergoing some revival. While many countries plan to rejuvenate their nuclear plants, countries like UK are presently decommissioning their old nuclear plants. Nevertheless, nuclear clean-up is a worldwide humanitarian issue (saving the environment for future generations) that must be faced by any country that has engaged in nuclear activities.

Despite the fact that nuclear activities around world are increased, it is estimated that many nuclear facilities world-wide will reach their maximum operating time and require decommissioning in the coming two or three decades. Thousands of tons of contaminated material (e.g. metal rods, concrete, etc.) need to be handled and safely disposed until they no longer possess a threat. This process involves not only the cleaning costs and human hours, but also the risk of humans being exposed to radiation. Decommissioning the legacy waste inventory of the UK alone, represents the largest environmental remediation project in the whole of Europe, and is expected to take at least 100 years to complete, with estimated clean-up costs as high as £220 billion (around $300 billion) [2]. Worldwide decommissioning costs are of order $trillion. Record keeping in the early days was not rigorous by modern standards, and there are now many waste storage containers with unknown contents or contents of mixed contamination levels. At the UK Sellafield site, 69,600 m^3 of legacy ILW waste must be placed into 179,000 storage containers. To avoid wastefully filling expensive high-level containers with low-level waste, many old legacy containers must be cut open, and their contents *sorted and segregated* [3]. This engenders an enormous requirement for complex remote manipulations, since all of this waste is too hazardous to be approached by humans.

The vast majority of these remote manipulation tasks in most of the nuclear sites around the world are still performed manually (by ageing workforce), where eminently skilled human operators control bulky mechanical Master-Slave Manipulator (MSM) devices. Usage of MSMs at nuclear plants dates back to at least 1940s and has changed slightly in design since then. Notably, few heavy-duty industrial robot manipulators have been deployed in the nuclear industry during the last decade (replacing MSMs) to be used for decommissioning tasks. However, most of these have predominantly been directly tele-operated in rudimentary ways [4]. An example can be seen in **Figure 1**, where an operator is looking through a 1.2 m thick lead-glass window (with very limited situational awareness or depth perception) and tele-operating the hydraulic BROKK robot arm by pushing buttons to control its various joints. Such robots, widely trusted in the industry due to their ruggedness and reliability, do not actually have proprioceptive joint encoders, and no inverse kinematics solving is possible for enabling Cartesian workspace control via a joystick. Instead, the robot's inverse kinematics has to be guessed from the operator's experience, which directly affects the task performance. It is not considered feasible to

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Figure 1. A BROKK robot, equipped with a gripper, being used for a pick and place task at the Sellafield nuclear site in UK. Human operator can be seen controlling the robot from behind a 1.6m thick lead-glass window which shields him from radiation, but significantly limits his situational awareness. For more examples, refer to www.sellafieldsites.com/solution/decommissioning.

retrofit proprioceptive sensors to the robots used in such environments: firstly, electronics are vulnerable to different types of radiation; secondly, the installation of new sensors on trusted machinery would compromise long-standing certification; thirdly, such robots are predominantly deployed on a mobile base platform (e.g. a rugged tracked vehicle) and have tasks often involving high-force interactions with surrounding objects and surfaces. Even if the robot had proprioceptive sensors, such high-force tools cause large and frequent perturbations to the robot's base frame, so that proprioceptive sensors would still be unable to obtain the robot's pose with respect to a task frame set in the robot's surroundings.

Recently, many efforts have been made to deploy tele-operated robots at nuclear disaster sites [5, 6]; with robots controlled by viewing through cameras mounted on or around the robot. Albeit the significant efforts made, overall throughput rates are deficient in tackling the real-world problems. Nevertheless, in the context of this chapter, the major difficulty is situational awareness while tele-operation, especially the lack of depth perception and effect of external disturbances on the operator (e.g. surrounding noise levels, temperature, etc.), which primarily questions accuracy and repeatability of the task being performed [7]. Also, since the legacy waste inventory that needs processing is astronomical, direct tele-operation by humans is time consuming and tedious. Up on noticing all these difficulties associated with direct tele-operation of robots in hazardous environments, it can be seen that many of the nuclear decommissioning tasks can be (semi-)automated up to an extent to improve the task completion time as well as performance.

A major helping block is the computer vision or vision sensing. Modern computer vision techniques are now robust enough to significantly enhance throughput rates, accuracy and reliability, by enabling partial or even full automation of many nuclear waste manipulation tasks. Moreover, by adopting external sensing (e.g. vision) not only provides quantitative feedback to control the robot manipulator but also enables to estimate its joint configuration effectively when the proprioception is absent [8]. Machine vision systems are already being used for a wide variety of industrial processes [9], where they provide information about scenes and objects (size, shape, colour, pose), which can be used to control a robot's trajectory in the task space [10, 11]. In the case of nuclear applications, previous studies have used vision information to classify nuclear waste [3] and to estimate radiation levels [12]. However, it is not known that any visual servoing techniques (using the tracked image information) been applied in the (highly conservative) nuclear domain. Nevertheless, we believe that a greater understanding of the underlying processes is necessary, before nuclear manipulation tasks can be safely automated.

This chapter mainly discusses how novice human operators can rapidly learn to control modern robots to perform basic manipulation tasks; also how autonomous robotics techniques can be used for operator assistance, to increase throughput rates, decrease errors, and enhance safety. In this context, two (common decommissioning) tasks are investigated: (1) point-to-point dexterity task, where human subjects control the position and orientation of the robot end-effector to reach a set of predefined goal positions in a specific order, and (2) box encapsulation task (manipulating waste items into safe storage containers), where human tele-operation of the robot arm is compared to that of a human-supervised semi-autonomous control exploiting computer vision. Human subjects' performance in executing both these tasks is analysed and factors affecting the performance are discussed. In addition, a vision-guided framework to estimate the robot's full joint state configuration by tracking several links of the robot in monocular camera images is presented. The main goal of this framework is to resolve the problem of estimating robot kinematics (operating in nuclear environments) and to enable automatic control of the robot in Cartesian space.

2. Analysis of tele-operation to semi-autonomy

The role played by robots in accomplishing various tasks in hazardous environments has been greatly appreciated; mainly for preventing the humans from extreme radioactive dosage [13, 14]. As previously stated, for many years they have been used to manipulate vast amount of complex radioactive loads and contaminated waste. Despite this fact, with the growing needs and technological developments, more new and advanced robotic systems continue to be deployed. This not only signifies the task importance but also questions the ability of human workers in operating them. Most of these robots used for decommissioning tasks are majorly tele-operated with almost no autonomy or even a pre-programmed motion as in other industries (e.g. automotive). Invariably there is regular human intervention for ensuring the environment is safely secured from any unsupervised or unplanned interactions. Most of this process is not going to change; however, some tasks in this process can be semi-automated to reduce the burden on human operators as well as the task completion time. In this section, we focus on analysing various factors affecting the performance of fully supervised tele-operated handling and vision-guided semi-autonomous manipulations.

2.1. Tele-operation systems

Tele-operation systems have been in existence as an ideal master-slave system or a client-server system. Many tele-operation based tasks have been used and their importance

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specifically in cases of human collaborative tasks has been widely studied [14]. These studies help in providing the importance to the human inputs and provide them with distinctive role to lead in more supervised tasks. In most of the cases the human acts as a master controlling or coordinating the movement to be handled by pressing buttons or by varying controller keys (e.g. joystick) and the robot acts as a slave (model) executing the commanded trajectories [15]. A typical example of such a tele-operation system using the joystick can be seen in **Figure 2**, where an operator uses the joystick as a guiding tool to move the robot arm or performing the orientation correction of the robot by viewing it from the live camera feed (multiple views of the scene). The robot then follows the instructions as advised and reaches the commanded position.

In an advanced tele-operation set-up, the operator feels the amount of force applied or the distance in which the gripper is opening and closing to grasp an object. Further, there are possibilities to include a haptic interface controller with specific force field induced while nearing an environmental constraint. These types of systems mainly assist operators in having full control of the tele-operators, when controlling them in congested environments. However, these systems are not fully exploited for performing nuclear manipulations and still most of the nuclear decommissioning tasks are executed using joysticks. In a more traditional model, the MSM device needs the human to apply forces directly. The major challenge associated is that no error handling is included with such systems (either MSM or joystick) and instead it is the task of human operator to correct any positional errors by perceiving the motion in a camera-display, which often induces task delays.

2.2. Tele-operated tasks for nuclear decommissioning

In the context of nuclear decommissioning, two commonly tele-operated (core-robotic) tasks are analysed: positioning and stacking. Maintaining the coherence with real nuclear scenario, these two tasks are simulated in our lab environment and are detailed below.

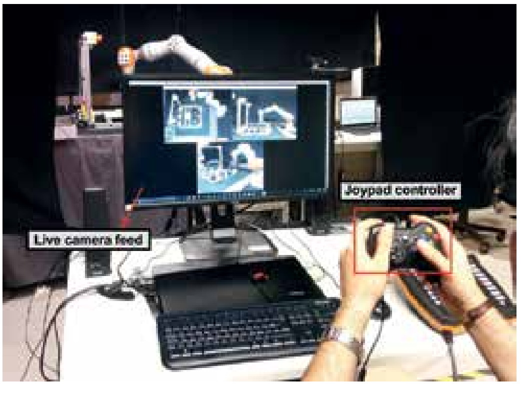

Figure 2. A human operator controlling the motion of an articulated industrial manipulator using joystick. The robot motion has been corrected by viewing it in the live camera feed.

2.2.1. Task 1: sequential positioning

This is one of the initial and majorly performed tasks, where an operator is required to manoeuvre the robot arm (end-effector) from a point to another in a specific order. While performing this task, the operators are required to control the positioning errors only from passive vision, i.e. by viewing at multiple camera displays. A special purpose tele-operation testbed containing multiple buttons has been designed to study this task (can be seen in **Figure 2**). For the sake of analysing human performance, multiple participants with almost none or limited robotic knowledge are recruited following specific criteria (explained in Section2.2.3). Each participant has been asked to move the robot end-effector from point-to-point in a designed order and while doing so, multiple parameters have been recorded (explained below) in order to analyse the task performance in terms of various effecting factors. Three specific points of action are chosen (buttons on the testbed) based on the kinematic configuration and to challenge the manipulability of the operator. Furthermore, a 'beep' sound is introduced to these three points such as to indicate the operator upon successful point-to-point positioning and completion of the task. The same three points are chosen for all the trials in order to evaluate the operator's performance over the course of repetitions. Each participant has been asked to repeat the task four times, where two trials are made in the presence of loud industrial noise such as moving machines, vibrations, etc. This has been done to analyse the operator performance in case of external environmental disturbances.

2.2.2. Task 2: object stacking

Stacking classified objects in an order into the containers is one of the vital tasks performed in the frame of decommissioning. Here it is assumed that objects (contaminated waste) have been classified beforehand and hence, waste classification process is not explained in this chapter. In general, stacking concurrently includes positioning and grasping. Underlying goal is to get hold of the (classified) objects positioned in the arbitrary locations. Operator while tele-operating has to identify the stable grasping location including collisions with the environment and has to stack the grasped object in a specific location or inside a bin. Similar to the previous task, this task has been designed to use passive vision and operator is able to control both robot and gripper movements from the joypad. However, since positioning and grasping collectively can be automated up to an extent, the task performance by direct human tele-operation is compared with a semi-autonomous vision-guided system (explained in next section). For analysing, three wooden cubes of size $4 \times 4 \times 4$ cm^3 are used as sample objects. In order to allow fair comparison, the objects to be stacked are positioned in the same locations for all trials and similar experimental conditions are maintained.

2.2.3. Data acquisition for performance analysis

Multiple factors are evaluated to analyse the human operators' performance and workload in accomplishing above mentioned tasks. A total of 10 participants (eight male and two female) were recruited with no prior hands-on experience or knowledge about the experimental setup. All the participants had a normal to corrected vision. Previously developed software [16] has been used to interface the robot motion control with a gaming joypad, which allows the

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operator to switch between and jog the robot in different frames (joint, base and tool) as well as to control the attached tool, i.e. a two finger parallel jaw gripper. An initial training was provided at the beginning of each task for each participant, focussing on detailing the safety measures as well as to get accustomed with the experimental scenario. Since passive vision has been used (emulating the real nuclear decommissioning environment), it was also necessary to ensure that the participants understand different camera views. Finally, the analysis has been performed by evaluating the following measures:

- *Observed measures*: These are intended to evaluate the operators' performance and are purely based on the data recorded during each task. The following factors are identified to estimate individual performance: success rate per task, task completion time and errors per task. These are detailed in **Table 1**.
- *Measures obtained from self-assessment*: These are intended to evaluate the operators' workload. To this purpose, *NASA Task Load Index* (NASA-TLX) forms are provided to each participant upon task completion, which involves questioning the user to rate their effort in terms of workload demand. The following measures are obtained from the completed forms: mental demand, physical demand, temporal demand, performance, effort, and frustration. The participant evaluates his/her individual performance in each task based on the influence or impact of the task and their individual comfort in pursuing them using the robot.

2.3. Semi-autonomous systems

Semi-autonomous systems are another prominent robot based approaches used for manipulation tasks in nuclear decommissioning [14]. The concept of semi-autonomy is quite similar to the tele-operation but with even more less effort or input from the human. The role of human in a semi-autonomous system is still a Master but handling only the supervisory part, i.e. initialising and monitoring. The operator gives the orders or decides the course of action to be performed by the robot, which are then executed by the system in a seemingly effortless response. For instance, human can identify the path to be followed by the robot and define that by means of an interface, which will be then executed by the robot. In some cases, the human operator can even define actions like grasping, cutting, or cleaning, etc. The system only needs the input in order to execute from the human instead of moving the entire robot like as in the previous case and in addition, since human being master can take over the control

Measure	Description
Total trials	Total number of repetitions in each task
Success rate per task	$\frac{\text{Total trials} - \text{Collisions} - \text{Perceptual misses}}{\text{Total trials}}$
Task completion time	$\frac{\sum \text{Elapsed time (completed trials)}}{\text{Completed trials}}$
Errors per task	$\frac{\text{Collisions} + \text{Perceptual misses}}{\text{Total trials}}$

Table 1. Observed measures to analyse operators' performance.

at any point of time. Most of the semi-autonomous systems rely on the external sensory information (e.g. vision, force, etc.) of the environment. The use of vision based input to manipulate the tasks and to progress through the environment has been proven effective in many cases [17]. Using visual information as a feedback to control robotic devices is commonly termed as *visual servoing* and is classified based on the type of visual features used [18]. For the sake of analysing the performance of a semi-autonomous system as well to compare the human performance in case of stacking objects, a simple position-based visual servoing scheme has been developed as in Ref. [16] to automatically manoeuvre the robot to a desired grasping location and to stack objects. A trivial visual control law has been used in combination with a model-based 3D pose matching [19]. It is always possible to use a different tracking methodology and to optimise the visual controller in many aspects. Readers can find more details about this optimisation process in Ref. [20].

2.3.1. Stacking objects by visual servoing

Overall task is decomposed into two different modules: grasping and stacking, where the former involves automatic navigation of the robot to a stable grasp location, and the latter involves placing the grasped objects at a pre-defined location. It is assumed that the object dimensions are always available from the knowledge database and the vision system is pre-calibrated. The task of automatic navigation starts by operator selection of the object, i.e. by providing an initial pose (e.g. with mouse clicks) and can be accomplished by: tracking full (six DoF) pose of the objects and by commanding the robot to a pre-grasp location using this information. The optional pre-grasp location is required only when the camera is mounted on top of the robot end-effector in order to avoid any blackspots for the vision while the robot approaches the object. This location has to be selected such that the robot can always maintain a stable grasp by moving vertically downwards without colliding with any other objects in its task space. It is worth noticing that the operator possess full control of this process by visualising the task as well as robot trajectory. **Figure 3** shows different tracked poses of an object during this process of automatic navigation to pre-grasp location.

Once the object is stably grasped, the task of stacking will be initiated automatically. During this phase the system uses its knowledge of the location to stack, i.e. the location to release the

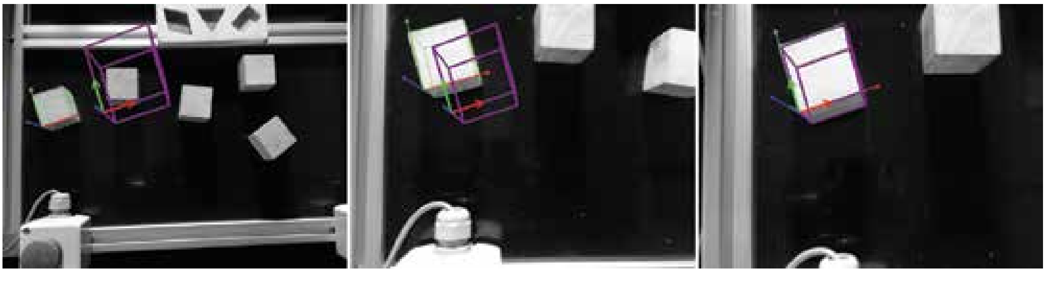

Figure 3. Series of images obtained during vision-guided navigation to grasp object 1 (first wooden cube). The wireframe in space represents the desired or initialised pose provided by the human and the wireframe on object represents the pose tracked during various iterations. Visual servoing goal is to minimise the error between those two poses such that they match with each other.

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object, the number of objects already stacked and the dimensions of object being handled. Once the object is released or stacked, the robot will return to a defined home position and waits for the next human input.

2.3.2. Task analysis

Analogous to tele-operation, the task performance has been analysed by monitoring various factors such as collisions, success rate and task completion time. The robot has been commanded to stack all three blocks 10 different times and during which it only uses the images from on-board camera. In order to achieve good performances especially when using artificial vision, environmental lighting has been made seemingly stable throughout the task, which is also the case for tele-operation.

3. Vision-guided articulated robot state estimation

The overall goal of this section is to increase the operating functionality of under-sensored robots that are used in hazardous environments. As mentioned, most of the heavy-duty industrial manipulators that operate in hazardous environments do not possess joint encoders, which make it hard to automate various tasks. An inability to automate tasks by computer control of robot motions, not only means that task performances are sub-optimal, but also that humans are being exposed to high risks in hazardous environments. Moreover, during the execution of tasks, robots must interact with contact surfaces, which are typically unknown a-priori, so that some directions of motion are kinematically constrained. Our premise is that adopting external sensing, which is remote from the robot (e.g. vision using remote camera views of the robot) offers an effective means of quantitative feedback of the robot's joint configuration and pose with respect to the scene. Note that cameras can be rad-hardened in various well-known ways, and even simple distance of a remote sensor, away from the radiation source, greatly reduces impact on electronics via inverse-square law. Vision-based proprioceptive feedback can enable advanced trajectory control and increased autonomy in such applications. This can help remove humans from harm, improve operational safety, improve task performance, and reduce maintenance costs [16].

3.1. Related work

Vision information is used as the backbone of this concept and solely relying on which, the entire robot joint configuration is derived. Usually, this can be misinterpreted with classical visual servoing methods, where the robots are visually controlled using the information obtained from proprioceptive sensors. Visual servoing literature predominantly relies on accurately knowing robot states derived from joint encoders. However, Marchand et al. [21]. demonstrated an eye-to-hand visual servoing scheme to control a robot with no proprioceptive sensors. In order to compute the Jacobian of the manipulator, they estimate the robot configuration. Thus, they feed the end-effector position to an inverse kinematics algorithm for the non-redundant manipulator. In Ref. [22], a model-based tracker was presented to track and estimate the configuration as well as the pose of an articulated object.

Alongside visual servoing, pose estimation is also related to this section. Pose estimation is classically defined for single-body rigid objects, with six DoF. On the other hand, articulated objects are composed of multiple rigid bodies and possess higher DoF (often redundant). There are also a number of kinematic (and potentially dynamic) constraints that bind together the bodies belonging to kinematic chains. Further, these constraints can also be used to locate and track the chain of robot parts. A variety of ways to track articulated bodies can be found in Refs. [23, 24]. These authors mainly focused on localising parts of the articulated bodies in each image frame, and not on the estimation of joint angles between the connected parts. Additionally, much of this work focussed on tracking parts of robots, but made use of information from the robot's joint encoders to do so, in contrast to the problem posed. A real-time system to track multiple articulated objects using RGB-D and joint encoder information is presented in Ref. [25]. A similar approach was used in Ref. [26] to track and estimate the pose of a robot manipulator. Some other notable examples can be found in Ref. [27], where the authors propose to use depth information for better tracking of objects. Recently, an approach based on regression forests has been proposed to directly estimate joint angles using single depth images in Ref. [28]. However, most of these methods require either posterior information (e.g. post-processing of entire image sequences offline to best-fit a set of object poses), or require depth images, or must be implemented on a GPU to achieve online tracking.

In summary, the use of depth information alongside standard images can improve the tracking performances. However, it also increases the computational burden and decreases robustness in many real-world applications. Our choice of using simple, monocular 2D cameras is motivated by cost, robustness to real-world conditions, and also in an attempt to be as computationally fast as possible.

3.2. Chained method to estimate robot configuration

Similar to the semi-autonomous task from Section2.3.1, a CAD model-based tracker based on *virtual visual servoing* is used to track and identify the poses of various links of the robot. We also assume that:

- the robot is always in a defined home position before initialising the task, i.e. its initial configuration is known; and
- the robot's kinematic model is available.

In turn the tracked poses are related with various transformations to estimate the entire robot configuration. There are two ways to relate camera to each tracked part, a direct path whose relationship is given by the tracking algorithm, and another path using the kinematic model of the robot. These two paths kinematically coincide, thus we enforce the following equalities to estimate the state of the robot:

$$ {}^{C}\mathbf{M}_{obj_i} = {}^{C}\boldsymbol{T}_0\, {}^{0}\boldsymbol{T}_{obj_i}(\boldsymbol{q}) \tag{1} $$

Where, ${}^{C}\mathbf{M}_{obj_i}$ is the homogenous transformation from camera to object frame, ${}^{C}\boldsymbol{T}_0$ is the transformation from camera to world frame and ${}^{0}\boldsymbol{T}_{obj_i}(\boldsymbol{q})$ represents the transformation from world to object i frame parametrised over the joint values $\boldsymbol{q}$, i.e. ${}^{0}\boldsymbol{T}_{obj_i}(\boldsymbol{q})$ embeds the kinematic model of the robot. We track four different links of the robot as shown in **Figure 4(b)**. Therefore, for each tracked robot part, we get:

$$ {}^{C}\mathbf{M}_{obj_1} = {}^{C}\boldsymbol{T}_0\ {}^{0}\boldsymbol{T}_1(\boldsymbol{q}_1)\ {}^{1}\boldsymbol{T}_{obj_1} \tag{2}$$

$$ {}^{C}\mathbf{M}_{obj_2} = {}^{C}\boldsymbol{T}_0\ {}^{0}\boldsymbol{T}_1(\boldsymbol{q}_1)\ {}^{1}\boldsymbol{T}_2(\boldsymbol{q}_2)\ {}^{2}\boldsymbol{T}_{obj_2} \tag{3}$$

$$ {}^{C}\mathbf{M}_{obj_3} = {}^{C}\boldsymbol{T}_0\ {}^{0}\boldsymbol{T}_1(\boldsymbol{q}_1)\ {}^{1}\boldsymbol{T}_2(\boldsymbol{q}_2)\ {}^{2}\boldsymbol{T}_3(\boldsymbol{q}_3)\ {}^{3}\boldsymbol{T}_4(\boldsymbol{q}_4)\ {}^{4}\boldsymbol{T}_{obj_3} \tag{4}$$

$$ {}^{C}\mathbf{M}_{obj_4} = {}^{C}\boldsymbol{T}_0\ {}^{0}\boldsymbol{T}_1(\boldsymbol{q}_1)\ {}^{1}\boldsymbol{T}_2(\boldsymbol{q}_2)\ {}^{2}\boldsymbol{T}_3(\boldsymbol{q}_3)\ {}^{3}\boldsymbol{T}_4(\boldsymbol{q}_4)\ {}^{4}\boldsymbol{T}_5(\boldsymbol{q}_5)\ {}^{5}\boldsymbol{T}_6(\boldsymbol{q}_6)\ {}^{6}\boldsymbol{T}_{obj_4} \tag{5}$$

The state of the robot is estimated by imposing the equality given in the previous equations, and casting them as an optimisation problem. Since the robot's initial configuration is known, it is used as a seed for the first iteration of the optimisation problem and the robot's kinematic model is used to compute ${}^{0}\boldsymbol{T}_{obj_i}(\boldsymbol{q})$. The optimisation problem is then stated as:

$$ \underset{\boldsymbol{q}}{\text{minimise}} \sum_i \boldsymbol{e}_i(\boldsymbol{q}) \text{ Subject to } |\boldsymbol{q}_i| < \boldsymbol{q}_{max} \tag{6}$$

Where,

$$ \boldsymbol{e}_i(\boldsymbol{q}) = vec\left({}^{C}\mathbf{M}_{obj_i} - {}^{C}\boldsymbol{T}_0\ {}^{0}\boldsymbol{T}_{obj_i}(\boldsymbol{q})\right) \tag{7}$$

represents an error in the difference of the two paths shown in **Figure 4(a)** to define a transformation matrix from the camera frame to the tracked objects frames, and $\boldsymbol{q}_{max}$ is the joint limit. **Figure 4(a)** also depicts the overall estimation schema. The trackers return a set of matrices, i.e. one for each tracked part. The sets of equations coming from each of the four ${}^{C}\boldsymbol{M}_{obj_i}$ can be used in series to solve for subsets of joint variables, which can be called the 'chained' method. From **Figure 4(a)**, the following dependencies can be observed for each tracked object:

- first object's position obj_1RF depends only on q_1;
- second object's position obj_2RF on q_1 and q_2 ;
- third object's position obj_3RF on q_1, q_2, q_3 and q_4 ;
- finally, fourth object's position obj_4RF depends on all the six joints.

As pointed in **Figure 4(c)**, two cylindrical and two cuboid-shaped parts of a KUKA KR5 sixx robot are tracked for proof of principle. However, this choice is not a limitation, and a variety of different parts could be chosen. Nevertheless, the parts must be selected such that they provide sufficient information about all joints of the robot. Even though the concerned robot possesses proprioceptive sensors, they are not used in the estimation schema.

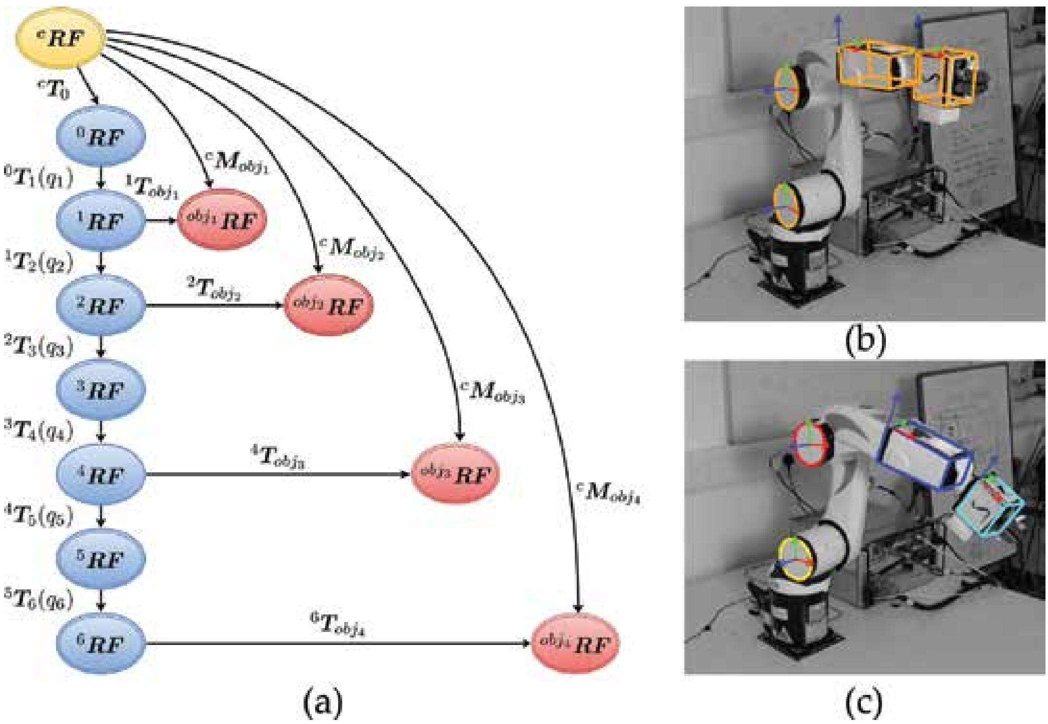

Figure 4. Illustration of the estimation work and tracking. (a) Shows the proposed state estimation model. Nodes represent reference frames and are classified top node represents camera frame, left aligned nodes represent robot frames and the right distributed nodes represent tracked object frames. The two paths leading to each tracked object frame from the camera reference frame can be seen. (b) Sequence of robot links to track and (c) tracked links in a later frame.

The chained method uses each object to estimate only a subset of joint values. These, in turn, are used as known parameters in the successive estimation problems. For example, q_3 and q_4 can be retrieved using obj_3, as in:

$$\underset{q_3\, q_4}{\text{minimise}}\ \boldsymbol{e}_3\left(q_1\, q_2\, q_3\, q_4\right) \text{ Subject to } |\boldsymbol{q}_j| < \ \boldsymbol{q}_{max},\ j = 3.4 \tag{8}$$

In the similar fashion, other joints, i.e. q_1, q_2, q_5 and q_6 can be estimated using Eq. (6). Using only one object at a time, the quality of configuration estimation becomes highly dependent on the tracking performance for each individual part. Although it induces the advantage of being robust to single part tracking failure (producing outliers that influence the estimation of only the relative subset of angles), it adds the disadvantage of propagating the possible error of already estimated angles in subsequent estimations.

4. Experimental studies

Two different sets of experiments are conducted to validate human factor performance (explained in Section2) and to evaluate the vision-guided state estimation scheme (explained in Section3). It is worth noting that all the experiments reported are conducted in the frame of hazardous environments. For the first set of experiments, an industrial collaborative robot KUKA lbr iiwa 14 r820 with seven DoF is used, to which a Schunk PG-70 parallel jaw gripper is connected as a tool. On the other hand, the second set of experiments is conducted using an industrial low-payload robot KUKA KR5 Sixx with six DoF. The commercial Logitech c920 cameras have been used for both experiments: for the first set of tests it is mounted on the tool and is used only for semi-autonomous tasks whereas for the second set, the camera is placed inside the workspace such that all the robot links are visible to accomplish the task. In either case, same work computer has been used and the communication between: robot and PC is realised over Ethernet, gripper and PC is realised over serial port, and camera and PC is realised over USB. ViSP library [29] has been used for the purpose of fast math computation and scene visualisation.

4.1. Analysing human factor performance

Recalling, various measures are identified to evaluate the human performance in performing different tasks. Later, operator performance is evaluated with a semi-autonomous system. In this context, first the experimental results evaluating 10 novice participants (eight male and two female) of age 30 ± 5.5 (mean $\pm \sigma$) performing the two tasks are reported. The performance of each participant is analysed and evaluated based on both the observed and self-reported measures as explained in the Section2.2.3.

4.1.1. Observed measures analysis

The observed measures of each participant have been categorized based on the time taken by the participant to fulfil the task, success rate in achieving it and the performance over the number of trials.

4.1.1.1. Sequential positioning: point-to-point dexterity task

The task was to push and release the buttons (upon hearing a beep sound) in a sequential order by jogging the robot. If the robot's tool collided with any object in the environment or if there is a perceptual miss in the target, the trial was considered as a failure. In total there are four trials for a participant. In order to increase the challenges in the task as well as to replicate a real industrial scenario, the final two trials are conducted with an audio track of industrial environment. The noise in the audio comprises of multiple tracks with continuous machinery sounds and intermittent sounds like welding, clamping, etc. **Figure 5(a)** and **(b)**, illustrates the average time taken by all the participants in reaching the desired points, i.e. in pushing the three buttons. The minimum and maximum values of all the participants are also indicated in the **Figure 2**. The influence of noise is also observed and the averaged time taken by each participant in pushing the three buttons is shown in **Figure 5(b)**. The normalised success rate computed among all participants in case of the first two trials (without noise) is 0.95 and for the latter two trials (with noise) is 0.87. Upon observing the results, it can be seen that there is a considerable amount of effect by the environmental noise on human operator in accomplishing the task. Mainly, from operators' experience, it has been found that the intermittent noise distracted their attention from the task and consequently led to reduced performance.

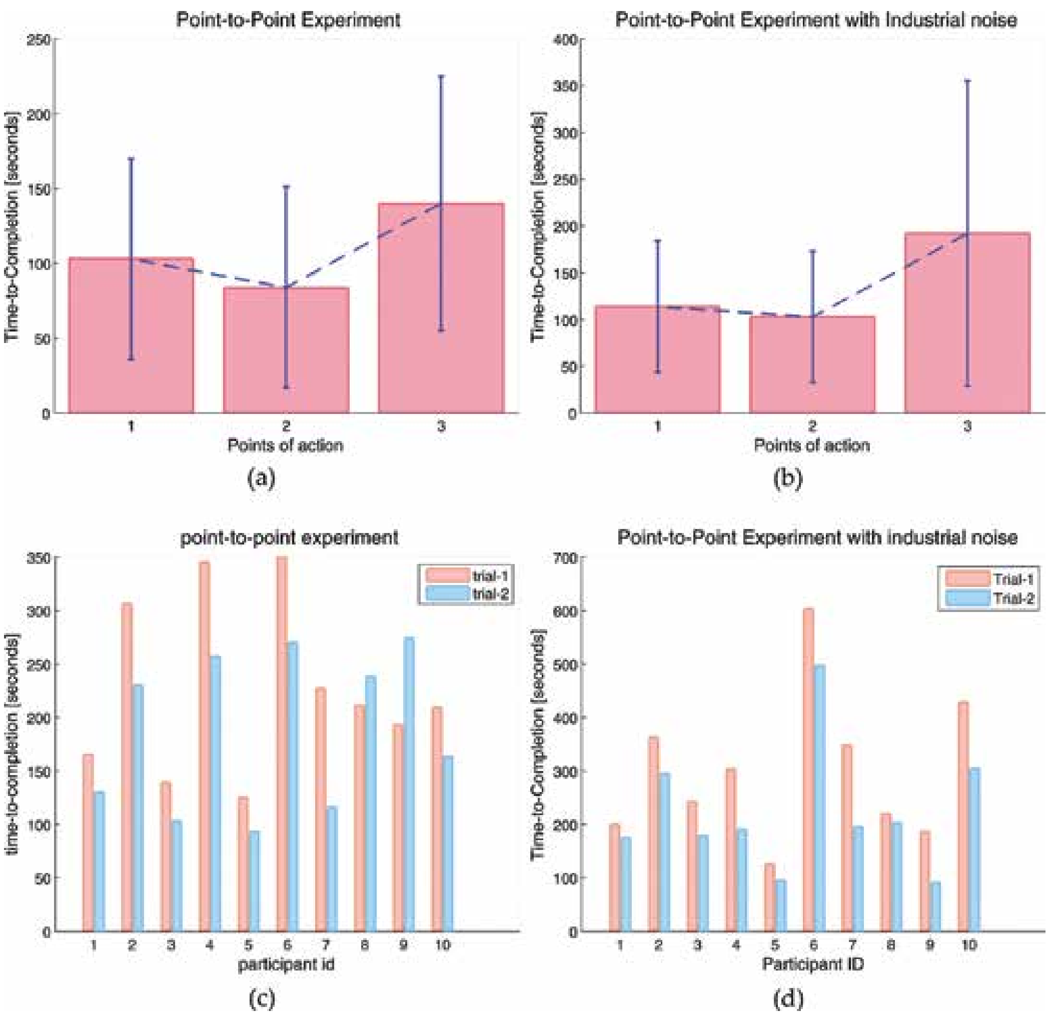

Figure 5. Illustration of the human performance in accomplishing point-to-point task over different trials at multiple conditions, i.e. in the absence and presence of environmental noise. (a) and (b) shows the average time spent in reaching multiple points of action on the test rig without (first two trials) and with (latter two trials) industrial noise, respectively. Since the location of button-3 is quite challenging to reach, participants spent more time with this point. (c) and (d) shows participants' individual time taken among all trials without and with noise, respectively. Effect of noise on task performance is clearly evident.

On the other hand, operators' learning over the tasks is also analysed. **Figure 5(c)** and **(d)** shows the time to completion for each participant over multiple trials. The repeated measure analysis of variance (ANOVA) was used on the time-to-completion data in order to evaluate whether the performance significantly changed or not across the trials. ANOVA revealed that there was a significant learning effect across all four trials. From manual observation, for example, consider participants eight and nine whose performance reduced from trial-1 to trial-2. However, as a proof of learning, the same participants' performance improved over the next two trials (even in the presence of noise). Interestingly, individual performance is

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affected by the task complexity, which is noticeable by analysing the time-to-completion in **Figure 5(a)** and **(b)**. All the participants find it significantly easy to reach the points of action 1 and 2, where the robot end-effector is required to be pointing down, i.e. normal to the ground plane. Task learning is clearly visible among these two trials. However, the performance reduced (even after learning) while approaching the third point of action, where the robot end-effector needs to be positioned parallel to the ground plane, which requires operator's intelligence in solving the robot's inverse kinematics so as to move appropriate joints in accomplishing the task.

4.1.1.2. Object stacking task

This task is to stack multiple objects at a defined location by controlling the robot motion. Similar to the previous, if the robot's tool collided with any object in the environment or if there is a perceptual miss in the target or if the object is not stably grasped or if the object is not successfully stacked; the trial was considered as a failure. In total, there are three trials for each participant. Since this task has been compared with semi-autonomy, all the trials are performed at noisy conditions. **Figure 6(a)** shows the average time taken among the trials by the participants in accomplishing the task and **Figure 6(b)** illustrates the individual performance. The normalised success rate computed among all participants is 0.74, which is comparatively less than the previous task. Also due to task complexity, the rate of perceptual misses observed were higher (mainly due to passive vision), specifically while positioning initial block at the specified location. Similar to the previous, ANOVA has been used to identify the learning among trials. Even though it returned significant learning behaviour, visually it can be seen that only 6 out of 10 participants (one partial) improved over trials. Also, it has been observed that many participants struggled matching or registering the camera views, which led to environmental collisions and thus leading to task failures or

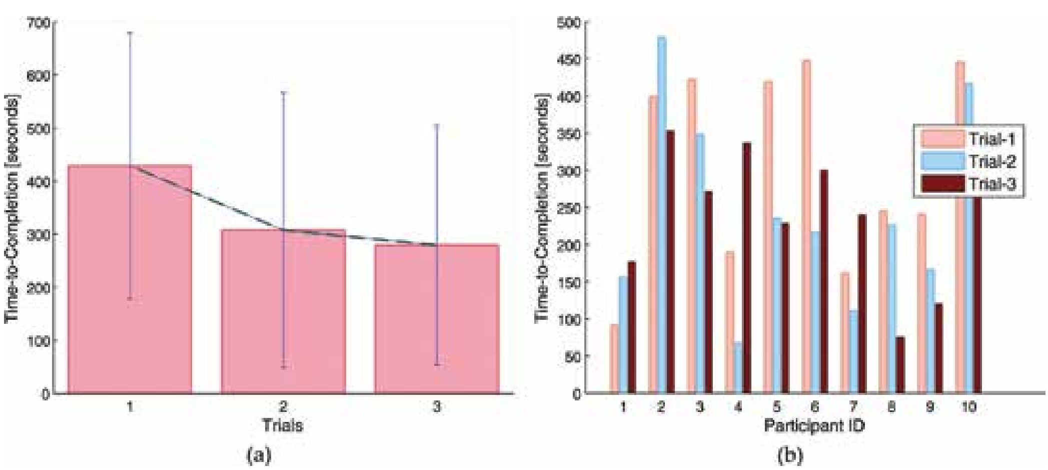

Figure 6. Illustration of the human performance in accomplishing stacking task over multiple trials. (a) Shows the average time taken among three different trials. Significant learning behaviour can be seen. (b) Illustrates the participants' individual task performance.

delays. These results clearly suggest the difficulties a human operator face in accomplishing a systemised task and therefore, the need for automation.

4.1.2. Self-assessed measures analysis

NASA TLX model was used as a base analysis for the self-reported measures. Each participant evaluated the task based on the following criterions: Mental demand, Physical demand, Temporal demand, Performance, Effort, Frustration. Two new parameters were also considered for task 1, i.e. the audio and video stress. **Table 2** and **Figure 7** report the results for both the tasks.

It is evident from the results, that all the participants found the task two to be more demanding. The Mental demands are significantly high for both the tasks, when compared with other

Self-reported measures	Task 1	Task 2
Mental demand	57.5 ± 21.24	71.5 ± 21.22
Physical demand	53.5 ± 32.14	60 ± 19.86
Temporal demand	57.5 ± 20.85	58 ± 20.30
Performance	40.5 ± 25.10	45.5 ± 18.63
Effort	50.5 ± 24.43	71.5 ± 16.17
Frustration	6.9 ± 4.33	10.6 ± 4.32
Total work load	**294 ± 29.08**	**359.5 ± 19.63**
Influence of audio	57 ± 23.47	-
Influence of video	55 ± 20	-

Table 2. Self-assessed measures for both the tasks.

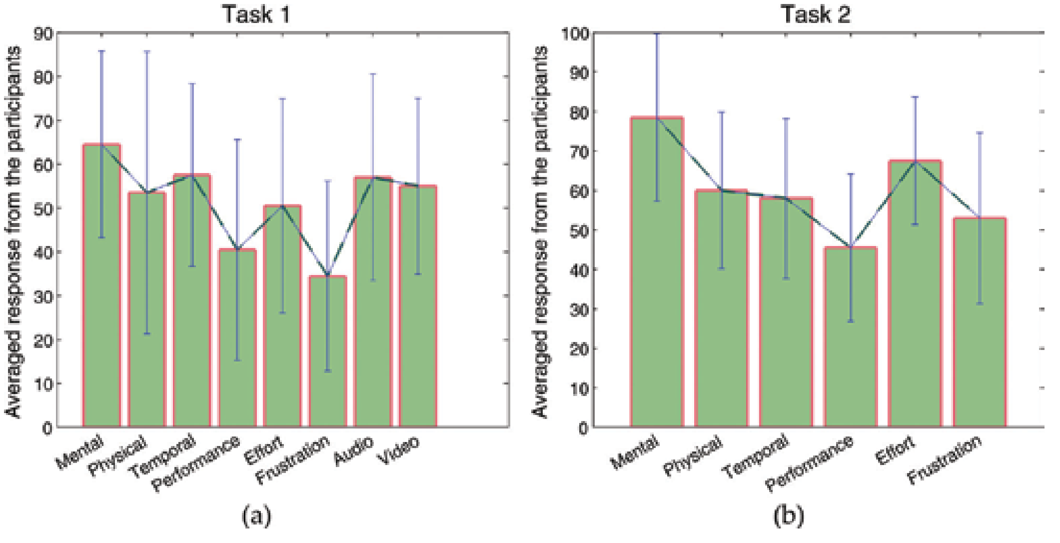

Figure 7. Bar charts illustrating the averaged performance of the participants using self-reported measure, NASA TLK for (a) task 1 and (b) task 2. An additional audio and video impact was evaluated specifically for task 1.

sub-scales. This seems to reflect that the tasks required participants to construct the 3D perception of the remote workspace through the 2D images of the live camera-feeds. At the same time, participants also needed to control the robot arm by tele-operation, which is the 2D space configuration and intuitively difficult to operate corresponding to the 3D space. These operations require high cognitive load and functioning. Besides, Task 2 requires more precise movements in handling the objects, grasping them in a suitable position such that they can be stacked one above the other. The task complexity and the lack of experience in using the robotic tools resulted in the participants feeling the impact. On the contrary, the physical demands and frustration were relatively low, suggesting that the tele-manipulation could reduce the physical tiredness for such repetitive tasks. This trend might depend on the experimental design, i.e. no-time limit for the completion. Participants could focus more on their performance rather than the temporal demand. In addition, it can be seen again from **Figure 7(a)** the effect of surrounding audio and video live feed on human operator.

4.1.3. Analysis of semi-autonomous block stacking

These set of experiments are conducted to compare and evaluate the performance of a semi-autonomous system (explained in Section2.3.1). As mentioned before, this task consists of automatic navigation and grasping of blocks using vision feedback, and stacking blocks at a predefined location. In order to have a fair evaluation, the blocks were placed in similar locations as for the tele-operated task. Trackers are automatically initialised from the user defined initial poses. Then the robot has been automatically navigated to the pre-grasp pose, which is accomplished by regulating the positional error. **Figure 8(a)** and **(b)** show respectively the robot grasping first object and the final stacked objects. **Figure 8(c)** shows the time taken to stack three objects over 10 trials. On average the system requires 49.3s to stack three objects, which is almost times faster than the time taken by a human operator in accomplishing the same. Similar to the direct human tele-operation, this task has also been monitored for collisions and failures. Even though no collisions are observed, the task failed during 5th and 9th

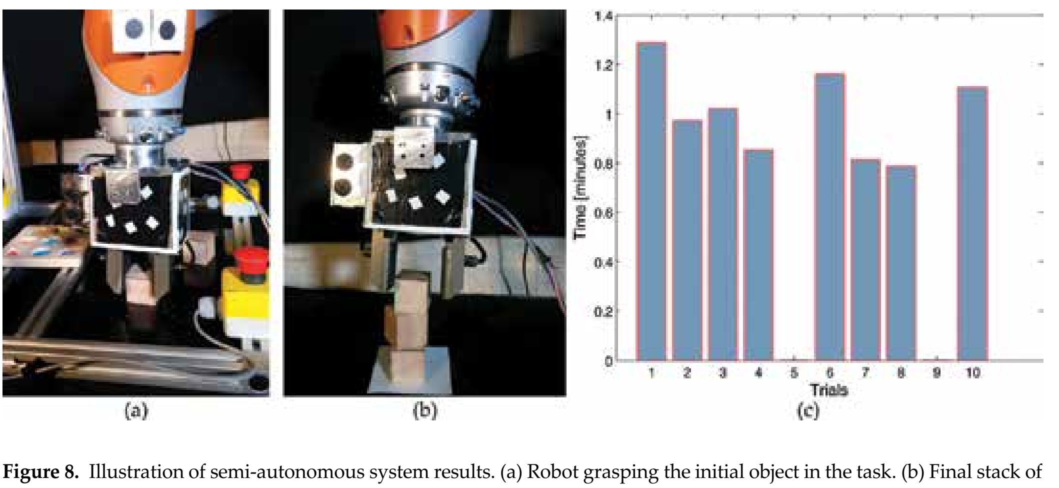

Figure 8. Illustration of semi-autonomous system results. (a) Robot grasping the initial object in the task. (b) Final stack of three objects in the specified location (white square area). (c) Overall time taken for semi-automated block stacking during 10 trials.

trials due to tracking error. Hence, the overall performance directly depends on the success of visual tracking system. Unlike with human tests, there were no shortcomings in the depth perception, which we think is the main reason behind reliable performance. However, in either of the cases, i.e. both semi-autonomous and human tests, integrating tactile information with grasping can improve the overall system performance.

4.2. Robot state estimation results

Two series of experiments are conducted. Firstly, the precision of the implemented chained method in estimating the robot configuration is assessed by commanding the robot in a trajectory where all joints are excited. During which the vision-estimated joint angles are compared to the ground-truth values obtained by reading positional encoders. Next, the vision-derived robot's configuration estimates are used in a kinematic control loop to demonstrate the efficiency in performing Cartesian regulation tasks. For this purpose, a classical kinematic controller of the form given by Eq. (9) has been implemented.

$$\dot{q}_{ref} = J^{\dagger}(q)(K_p e) - (K_D \dot{q}) \tag{9}$$

where, $\dot{q}_{ref}$ is the desired/reference velocity, and $J^{\dagger}(q)$ is the pseudo-inverse of the the robot Jacobian computed using our estimated joint configuration. K_p and K_D are proportional and derivative gain matrices, respectively. Since the robot is controlled in positional mode, Eq. (9) is integrated numerically to generate control commands.

4.2.1. Estimating robot's configuration by chained method

Figure 9(a) shows the arbitrarily chosen trajectory to analyse the estimation efficiency. Since only one camera is used to track the robot, the trajectory has been chosen such that the entire

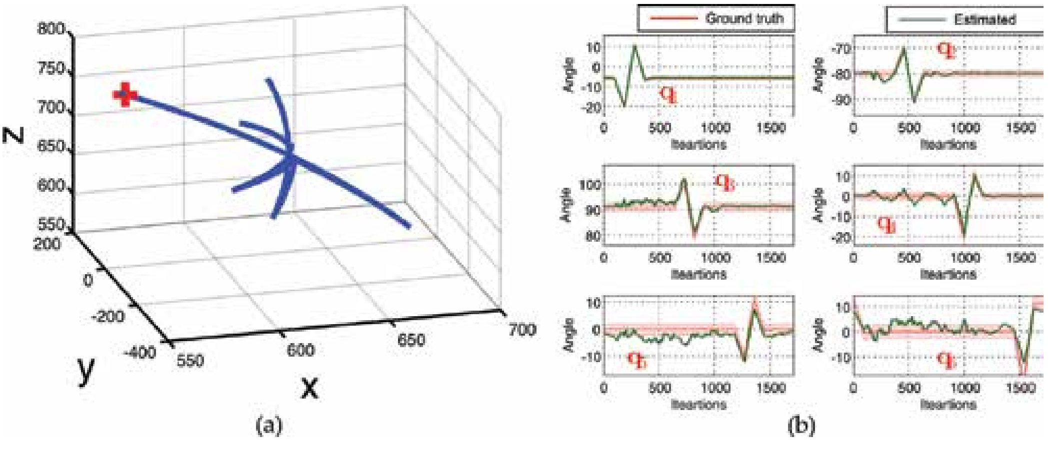

Figure 9. (a) Selected trajectory to evaluate robot state estimation. It has been chosen such that all the joints of the robot are excited. (b) Estimated and ground-truth joint angles during the trajectory (trial 3). Angles are expressed in degrees.

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tracked robot's links are visible throughout the trajectory. In order to perform the quantitative analysis, the robot has been commanded to execute the trajectory five times, repeatedly. The estimated and ground-truth values during the trajectory (for third trial) are shown in **Figure 9(b)**.

Joint	RMSE	Std.
q_1	0.581	0.269
q_2	0.801	0.777
q_3	1.372	1.054
q_4	1.508	1.504
q_5	2.512	1.634
q_6	4.106	2.636

Table 3. Performance analysis of the developed state estimation schema.

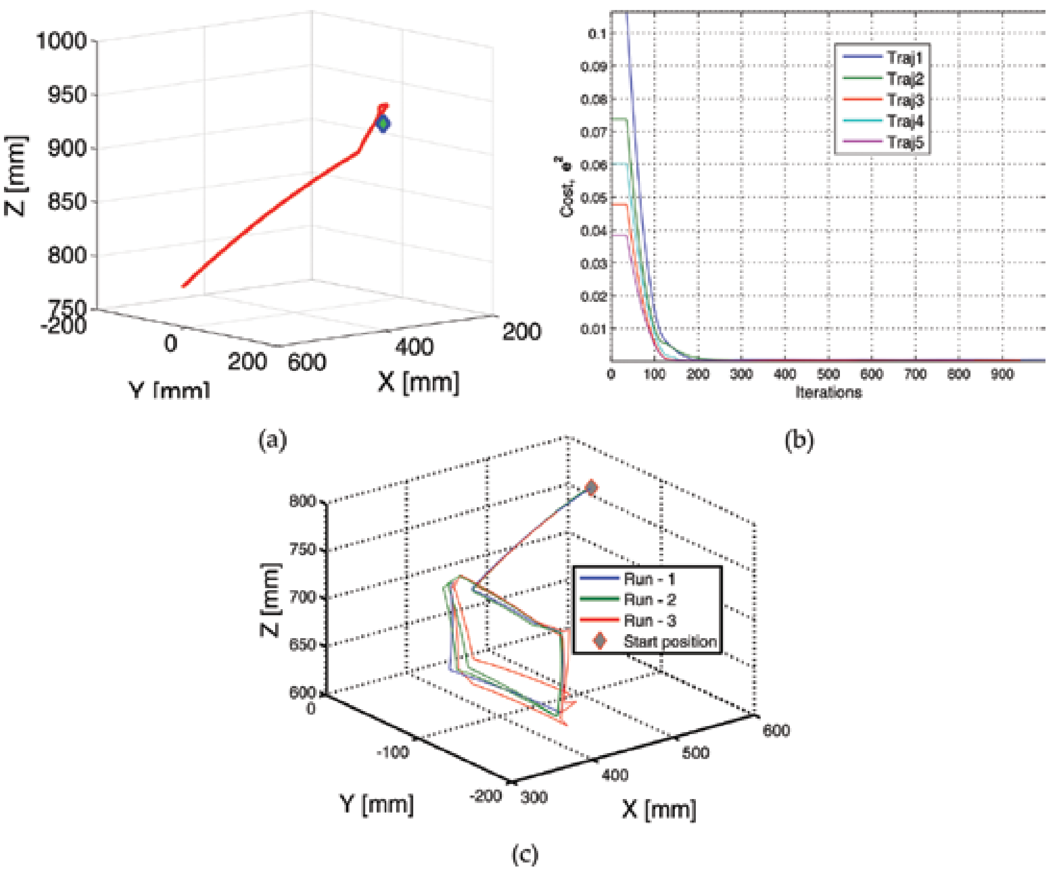

Figure 10. (a) Trajectory followed by the end-effector while reaching first goal position. (b) Evolution of controller costs during all five trajectories. (c) Square-perimeter trajectories followed by the end-effector. Diamond marker represents robot's starting position.

The average RMSE and standard deviation values over all trials are summarised in **Table 3**. On average, the estimation error is less than 4°, which clearly demonstrates the efficiency of the method in estimating robot's configuration through vision.

4.2.2. Cartesian regulation with vision estimates

Two different experiments are conducted. First, the robot end-effector has to be positioned automatically to five different goal positions using vision estimates and second, the robot was required to move its end-effector along a trajectory tracing out the perimeter of a square. Square corner locations in robot world frame are supplied as targets. **Figure 10(b)** shows the controller [given in Eq. (9)] cost variations while positioning to the five goal positions and **Figure 10(c)** shows the square trajectory followed by the robot in three different runs. These results clearly demonstrate the robustness of the method.

5. Conclusion

This chapter investigated two different concepts in the scope of hazardous environments. At the first hand, human performance was evaluated in executing remote manipulation tasks by tele-operating a robot in the context of nuclear decommissioning. Two commonly performed tasks are studied using which, various measures are analysed to identify the human performance and workload. Later, the human subject performance has been compared with a semi-autonomous system. The experimental results obtained by simulating the tasks at a lab environment demonstrate that the human performance improves with training, and suggest how training requirements scale with task complexity. They also demonstrate how the incorporation of autonomous robot control methods can reduce workload for human operators, while improving task completion time, repeatability and precision. On the other hand, a vision-guided state estimation framework has been presented to estimate the configuration of an under-sensored robot through the use of a single monocular camera. This mainly helps in automating the currently used heavy-duty industrial manipulators.

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Section 4

Protecting Robots in Hazardous Places

Robot Protection in the Hazardous Environments

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Wenwu Cao and Zhijiang Du

Additional information is available at the end of the chapter

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Abstract

Rescue missions for chemical, biological, radiological, nuclear, and explosive (CBRNE) incidents are highly risky and sometimes it is impossible for rescuers to perform, while these accidents vary dramatically in features and protection requirements. The purpose of this chapter is to present several protection approaches for rescue robots in the hazardous conditions. And four types of rescue robots are presented, respectively. First, design factors and challenges of the rescue robots are analyzed and indicated for these accidents. Then the rescue robots with protective modification are presented, respectively, meeting individual hazardous requirements. And finally several tests are conducted to validate the effectiveness of these modified robots. It is clear that these well-designed robots can work efficiently for the CBRNE response activities.

Keywords: hazardous environment, robot protection design, mobile robot, CBRNE

1. Introduction

Response ability of chemical, biological, radiological, nuclear, and explosive (CBRNE) incidents is becoming more and more important. The hazards not only come from nature but also from humans, such as chemical weapons, collapsed coal mine, and the loss and leakage of radioactive materials. Once such disasters occur, it is crucial to figure out what has happened and how the incident develops. However, the condition and objects in the incident sites are always a great threat to humans, motivating unmanned systems to execute rescue tasks instead of people. Considering that hazardous environment has not only a bad influence to human fitness, but also can damage the unmanned systems. So, the protection technology of unmanned robots emerges into public vision.

In our research, there are several types of robots developed for dangerous environments: (1) Explosion-proof robot: the coal mine robot is a typical representative of explosion-proof robot. As the coal mine environment is filled with unstable areas and a variety of combustible gases, any small sparks can lead to a secondary explosion, so the explosion-proof design is an essential feature. (2) Biochemical sampling robot: the protection technology for such robot mainly comprises two aspects. One is to completely isolate the parts, which have a direct contact on dangerous sources. And the other is to carry out the waterproof design for decontamination process. (3) Radiation-resistant robot: radiation will cause irreversible damage to both electronic devices and rubber components of the robot, so designing a corresponding radiation-resistant layer is the foundation in the whole design process. (4) Fire-fighting robot: the remarkable characteristic of such robot is the strict temperature condition, which fluctuates between 80 and 200°C, so the additional requirement is to consider the protection methods against high temperature.

The remainder of the chapter is outspread in the following aspects: In Section 2, related work is stated and discussed. The working condition analysis and special protection design are presented from Section 3 to Section 6, corresponding to coal mine rescue robot, Biochemical sampling robot, radiation-resistant robot, and fire-fighting robot, respectively. Finally, Section 7 concludes the chapter and prospects for future work.

2. Related work

The CBRNE events may be released accidentally (e.g., industrial accidents or natural disasters) or intentionally (e.g., terrorist act), and rescue robots have been widely adopted in the rescue and intervention missions [1–3]. Besides individual protection requirements for different tasks, the common point is related with decontamination process, which requests the waterproof performance of the robot [4–6].

Compared with general intervention systems, coal mine search-and-rescue robot systems need to be explosion-proof and waterproof [7, 8], which is why few robot systems are employed in coal mine search-and-rescue tasks. Groundhog and Gemini-Scout robot were also utilized to detect underground coal mine situations [9, 10]. During the utilization procedure, the fact that current mine rescue robots had been reconstructed from generic mobile robots has been considered and discussed [11, 12].

Biochemical sampling robot is always discussed as a sub-topic of the CBRNE intervention robot. A tele-operated wheeled vehicle with an underwater hydraulic manipulator was presented to cope with the CBRN intervention missions in Ref. [13]. According to Guzman et al. and Schneider and Wildermuth [4, 14], the idea of modular platform was proposed where sensors could be exchanged and upgraded easily without touching the underlying base, which is similar to the decontaminable robot idea.

Until now, the world has already faced three serious nuclear accidents: the Three Mile Island accident in 1979, the Chernobyl reaction accident in 1986, and the Fukushima Daiichi accident in 2011 [15, 16], and teleoperated robots were used in all of these three accidents [17, 18]. As illustrated in Ref. [17], several robots were used in the Three Mile Island not only for photographic/radiological inspection, but also for tasks such as concrete sampling and decontamination process [18]. In contrast to the Three Mile Island accident, the robots applied in the Chernobyl nuclear plant nearly got nothing as the high dose rate [19, 20], directing to the idea of interchangeable functional agents. When the Fukushima accident happened, the Quince robot performed prominently in the task and entered the reactor buildings seven times for dose rate measurement and water sampling [16]. Other high-performance surveillance robots in recent years include HELIOS, developed by Prof. Hirose's group [21], and ROBOT, developed by Bennett, P.C [19].

Ajala M [22] proposed an indoor fire-fighting robot, which has the capability to climb stairs and negotiate several types of floor materials inside buildings. It can withstand very high temperature up to 700°C as long as 60 min using multiple thermal insulation technique. Kim J H et al. [23] presented a multispectral vision system of robots used sensor fusion between stereo thermal infrared (IR) vision and frequency modulated-continuous wave (FMCW) radar to locate objects through zero visibility smoke in real time.

3. Coal mine rescue robot

Search and rescue robots are widely used in the coal mine disasters [24–28]. As the coal mine environment is filled with various combustible gases, and any small sparks can lead to a secondary explosion, so the explosion-proof design is a necessary feature for the robot.

The mine rescue robot (MINBOT-II) developed in our laboratory is shown in **Figure 1**. The robot adopts the track-moving scheme with a pair of front and back swing arms, which can facilitate the efficient attitude adjustment, as well as obstacle crossing ability in the hostile environment. In addition, the swing arms adopted the modular design approach to reduce the weight of the integrated system, so they are easy to assemble and disassemble from the main track-body, forming different configurations as shown in **Figure 1**.

Figure 1. Modular structure of MINBOT-II. (a) Robot without arms; (b) Robot with front and back arms; (c) Actual coal mine robot.

3.1. Explosion-proof and waterproof design of coal mine rescue robot

Since the coal mine accident site is full of gas and coal dust, any spark may cause an explosion. Therefore, the apparatus working in coal mines must be designed based on explosion-proof technology [3, 7]. Since there is water in the coal mine, the rescue robot must be waterproof. A detailed description of the explosion-proof and waterproof design of the coal mine rescue robot will be discussed in this section.

3.1.1. Explosion-proof design of the mechanical system

The plane explosion-proof method, cylinder explosion-proof method, and gum-filling explosion-proof method are widely used in explosion-proof equipment. We applied these methods to design the mechanical system of the rescue robot, which is detailed in the following.

As discussed above, some electrical components, such as batteries, drivers, motors, and control systems, are nonintrinsically safe, thus they need to be packaged together in an explosion-proof box made of high-strength steel. For convenience of assembly and disassembly, the explosion-proof box is divided into three parts, and the interfaces between each part are designed using the plane explosion-proof technique, as shown in **Figure 2(a)**. The cylinder explosion-proof technique is employed to make the motor power output shaft explosion-proof. Taking the back shaft, which has double layer outputs, for example [as shown in **Figure 2(b)**], the output shaft has an explosion-proof area with a 0.2 mm space and a length of 30 mm, as indicated by the red lines in **Figure 2(b)**.

The explosion-proof box cannot be completely sealed due to the driving shaft, so the approach of filling inert gas is not feasible in the robot. However, we employed the gum-filling explosion-proof method in the battery box. As the gum is occupying the capacity in the battery box, the volume of flammable gases is sharply reduced. In addition to the principles listed

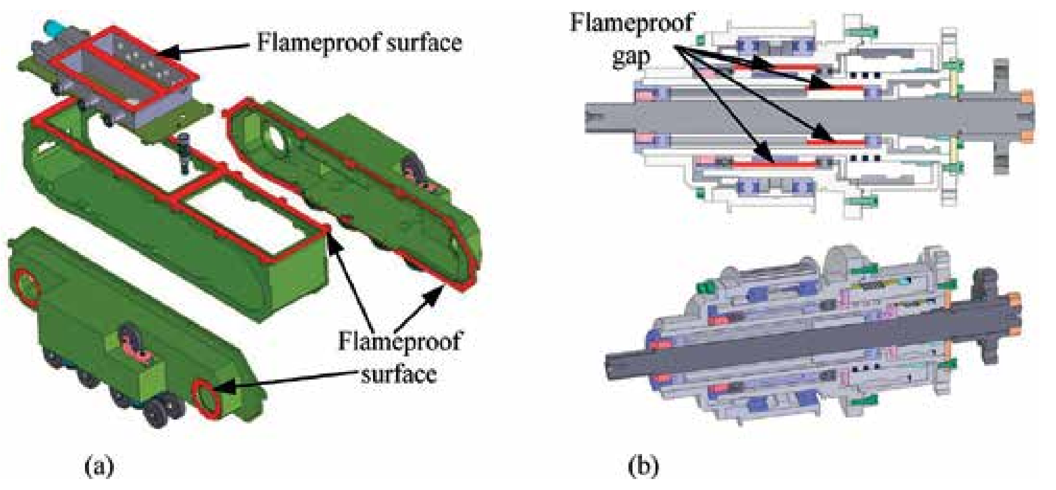

Figure 2. Explosion-proof designs of the mechanical system. (a) Plane anti-explosion design; (b) cylinder anti-explosion design.

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above, two issues should be carefully considered during the design: (1) The explosion-proof box should be capable of isolating the flammable gas, able to withstand impacts, and prevent damage or deformation during the deflagration in the environment with high-density flammable gas. (2) When an explosion happens inside of the robot system, the energy must be consumed and released very fast through an unloading channel. As an example, in this section, in the cylinder explosion-proof design, we lengthened the flame propagation distance and reduced the spread gap [shown in **Figure 2(b)**], so the flame energy is consumed in the tunnel and cannot ignite the flammable gas before it spreads outside the box.

3.1.2. Explosion-proof design of the electronic systems

The explosion-proof and intrinsically safe design of the robot's electrical system is illustrated in **Figure 3**. For intrinsically safe components that have to fulfill the intrinsically safe requirements, eliminating sparking and controlling temperatures are two main frequently used methods. The elimination of sparks is usually accomplished by limiting the stored energy (e.g., capacitance) in the circuit, while the internal short control method is commonly used to control the temperature. In addition, the intrinsically safe power supply is designed to isolate the power supply with explosion-proof devices, and the interactive signals between the intrinsically safe apparatus and explosion-proof apparatus are isolated in the physical chain. For the explosion-proof apparatus, the control system monitors high power consumption instruments and gives early warning of dangers.

3.1.3. Waterproof design of coal mine robot

To fulfill the water sealing requirements in coal mines, the protection grade of the robot has to be IP67. To realize this protection grade, the waterproof design is comprised of two methods, i.e., the whole body static sealing and the power output shaft dynamic sealing. For the static

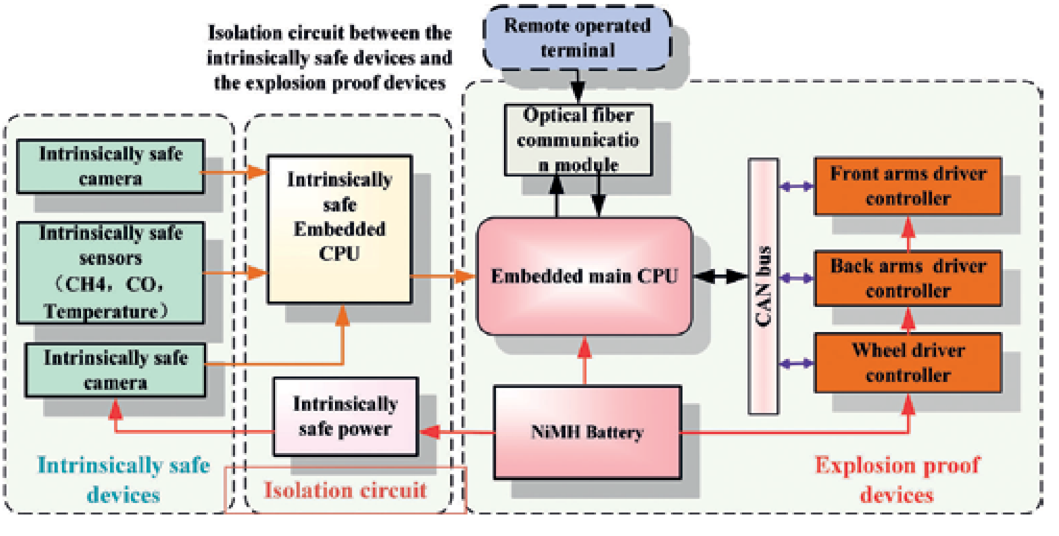

Figure 3. Explosion-proof diagram of the electrical system.

sealing method, the static waterproof (O-ring) is used at the transitions and connecting parts, while for movable components, such as the power output shaft, a dynamic sealing method is utilized, as shown in **Figure 4**. Springs are used between a static ring and a dynamic ring for compression, while the rubber sealing is used in the outer space. The rubber between the shells is the static sealing.

3.2. Coal mine environment tests

To test whether the proposed robots (MINBOT-II) fulfill the requirements to work in a coal mine environment, several test experiments were carried out by the laboratory of the Chinese Administration of Work Safety.

3.2.1. Explosion-proof test

A blasting test method was carried out to test the explosion-proof performance of the robot. In the test, the robot was filled with high-concentration CH4 after being assembled. It was then put into a room filled with flammable gas. Lighting the CH4 inside the shell, any fire leak and any deformation of the shell are impermissible, because they will make the flammable gas outside the shell (in the room) ignite.

The result of the explosion-proof test is shown in **Figure 5(a)**. The left frame shows the electrical connectors between the isolation box and the explosion-proof box after an explosion. The connectors, marked with a red circle, are undamaged. The right frame shows the flameproof surface of the explosion-proof box, marked with a red box. The surface is clean and undamaged after an explosion, and the test results show that the shell meets the explosion-proof requirements. The test results show that the shell meets the explosion-proof requirements.

3.2.2. Waterproof test

To validate the waterproof design of the robot, a static sealing waterproof test and a dynamic sealing waterproof test were performed. In the static sealing waterproof test, the shell was immersed in water, as shown in **Figure 5(b)**, the output shafts ran properly and leaking did not occur after 4 h. In the dynamic waterproof test, the shell was also immersed in water with all power output shafts running at different speeds, and leaking did not occur after 4 h.

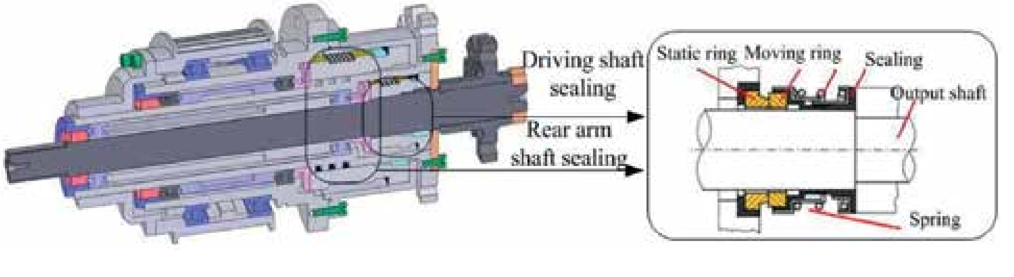

Figure 4. Dynamic sealing design of power output.

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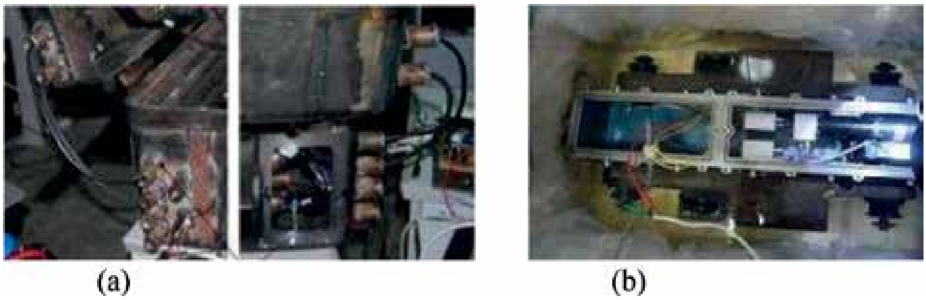

Figure 5. The result of (a) explosion-proof and (b) waterproof test.

4. Biochemical sampling robot

Biological and chemical hazards vary dramatically, such as the biochemical weapons, virus infections, leakage of toxic chemicals, and industrial discharges. As robot worked in this, environments will be polluted, and decontamination is a most popular method used to clean robot. Therefore, waterproof and special sampling tools should be designed.

The biochemical sampling robot developed in our laboratory is shown in **Figure 6**. Several functional equipment are integrated on the tracked mobile platform: a 6-DOF manipulator with a 1-DOF parallel gripper is mounted on the front of the robot; a set of sampling instruments is specifically designed and fixed in the middle of the robot and the end of the robot is provided with the communication system and pan-tilt vision system. In the following section, the protection design is presented in two aspects, namely decontamination design and sampling instrument design.

4.1. Protection design of biochemical sampling robot

4.1.1. Decontamination design of the biochemical sampling robot

When robot performs the sampling tasks in the biochemical environment, the hazardous material may contaminate the sampling robot, resulting into a new moving contaminated

Figure 6. The biochemical sampling robot and tests.

source. So, the decontamination process is an essential process when the robot completes the sampling task and traverse back to the safe domain. However, the decontamination procedure may cause damage to the sensitive parts of the robot. Therefore, two kinds of protection methods are commonly adopted: one is the shielding protection, namely placing a certain type of shielding material clothes, while painting protective materials is another method. Additionally, waterproof is also indispensable.

Apart from the shielding protection method of which the shielding clothes differ in specific hazardous situations, the painting method and waterproof method are carried out in the design process. (1) Considering the good permeability of several chemical reagents, Fluoride painting is employed to prevent the chemical reaction between the metal shell and the reagents. Moreover, side-protecting plates are added on the side of the track vehicle and swing arms, to prevent the hazardous materials (especially liquid) from sputtering into the track system, reducing the working intensity of decontamination task. (2) The waterproof design is similar to the coal mine robot illustrated above of which the protection grade against dust and water is IP67. The static waterproof method and dynamic sealing method are utilized for the robot (see part 3.1 for detailed information). Besides above protection approaches, the electrical interface which is exposed to the hazardous environment should adopt the aviation plug to ensure the connection reliability and waterproof performance.

4.1.2. Design of the sampling instruments

According to Guzman et al. [4], the identification of biochemical objects on a portable sensor unit is still not possible nowadays. Hence, samples in the hazardous domain should be acquired and taken back by sampling robot for further analysis in external laboratory. As the core devices of the biochemical sampling robot, the sampling tools and sampling container should be designed in the following aspects: (1) Sampling instruments should be conceived to meet the requirements of sampling different materials. (2) The position tolerance ability is considered as the positioning accuracy of the arm is affected by the vibration of the vehicle motion. (3) The sealing feature of sampling instruments is also required, due to the infectious and corrosive features of biochemical materials.

Through analysis and generalization of biochemical sample's properties, several typical sampling objectives can be summarized as follows: liquid on the surface, liquid in the deep hole, soil, powder, and little pieces of solid. According to the properties of different sampling objects, the corresponding instruments are designed with the modular method, as listed in **Table 1**. And the sampling instrument comprises sampling tool, sampling container, and position tolerance base, as shown in **Figures 7** and **8**.

To meet the position tolerance between sampling instruments and end-effectors, the mounting base can be divided into two layers: the aluminate alloy locking layer and the rubber tolerance layer. The former is attached to the sampling container with spring pin and stop pin, while the latter is fixed on the track vehicle and ensue the ability of position tolerance.

The sealing feature is also considered in the design. As illustrated in **Figures 7(f)** and **8(c)**, a built-in plastic tube is inserted into the sampling container, while a sealing plug is integrated into the sampling tool. When the sampling robot traverse back to the safe domain, the sealed samples

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Sampling objectives	Corresponding sampling tool	Attitude requirement		
		Sampling container	Sampling objective	Sampling process
Liquid on the surface	Dry cotton tool	√	○	○
Liquid in deep hole	Bucket tool	√	√	√
Soil	Shovel tool	√	√	√
Powder	Wet cotton tool	√	○	○
Small piece of solid	Tweezers tool	√	○	○

Table 1. Sampling tools and attitude requirements.

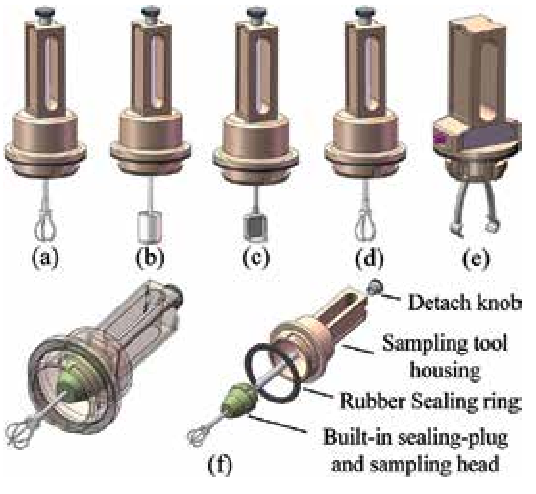

Figure 7. Five crucial kinds of sampling tools: (a) dry cotton ball tool, (b) bucket tool, (c) shovel tool, (d) wet cotton ball tool, (e) tweezers tool, (f) the components of sampling tools.

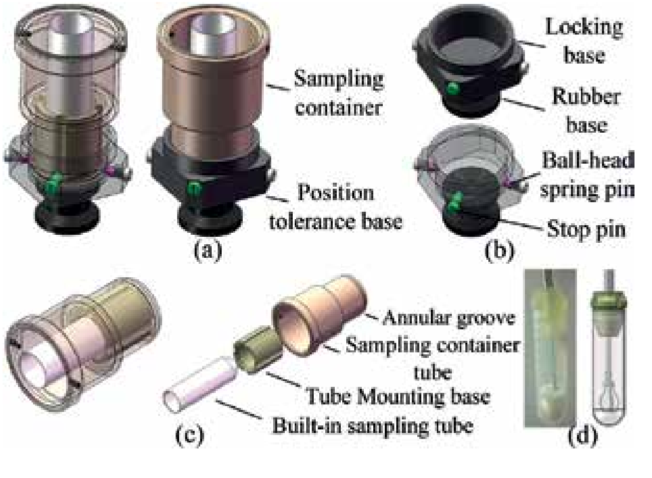

Figure 8. The sampling container and mounting base: (a) sampling container and mounting base, (b) position tolerance base, (c) the components of the sampling container, (d) built-in sealed sampling tube.

can be obtained directly through the detach knob mounted on the top of sampling tool, without worrying about the spread or damage of the hazardous samples, as shown in **Figure 8(d)**.

The rapidity ability of sampling task is considered in the mechanical design. The mechanical modification mainly focuses on the interface between end-effector and sampling tools, as well as the interface between sampling tool and sampling container. As shown in **Figure 9(a)**, a rectangular groove is added on the handle of the sampling tool, and a spiral structure is adopted for the interface between sampling tools and sampling containers. The former design feature ensures rapidity and reliability of the end-effector grasping process, while the later one realizes the position tolerance and the sealing performance between sampling tool and sampling container.

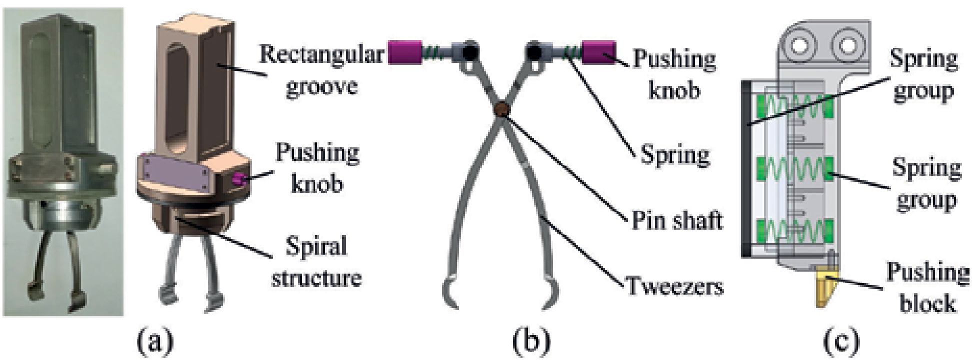

Figure 9. Quick change interface of the sampling tools. (a) Design features of tweezers tool, (b) clamping principle of tweezers tool, (c) quick change interface for th gripper.

4.2. Biochemical sampling test

As waterproof design of biochemical sampling robot is similar to coal mine robot, so the test is not illustrated here. The test for sampling process was conducted and the appliances include a set of sampling instruments, a sampling robot with a 6-DOF manipulator and a parallel gripper, a teleoperation box, and five kinds of samples, as shown in **Figure 6**. The autonomous step of pick and place sampling tools makes the sampling task faster and easier, while the sealing character of the built-in sampling tube works successfully.

5. Radiation-resistant robot

With the deepening utility of the nuclear energy, nuclear power is becoming a potential alternative energy solution, and nuclear power is also widely used in industry, health care, education, and other fields.

We designed a robot for handling out-of-control radioactive sources as shown in **Figure 10**. The robot employed a wheel-track hybrid mobile system with a front swing arm, equipped with a 7-DOF manipulator for redundant obstacle avoidance operations.

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Figure 10. The radiation-resistant robot.

5.1. Considerations for design process of radiation-resistant robot

In the above scenarios, radiation would cause irreversible damage to both electronic devices and rubber components of the robot, leading to the failure of radioactive emergency task, so radiation-resistant layer is the foundation and a dispensable step in the overall design process. However, the resistant materials are often very heavy; the optimization between radiation-resistant ability and mobility should be considered and weighted up. The development of radioactive protection methods and factors are synthesized [16–18], and the mission requirements of radiation-resistant robot are indicated in the following.

5.2. Protection design of radiation-resistant robot

The design process of the radiation protection is organized by the following sections. First, the mechanism of radiation is analysed. And then based on the common used radiation sources and shielding materials, we analyze and calculate the capacities of protection of different materials and determine the required location and thickness of shielding protection according to the sensitivity of different devices to radiation. Finally, by weighing the robot's mobile capability and radiation-resistant performance, the final shielding material and its corresponding thickness are determined, and the design of the shielding layer is completed.

5.2.1. Radiation mechanism of radioactive materials

Nuclear radiation mainly refers to the energy emission process of radioactive materials in the form of waves or particles through space. The generated electromagnetic waves mainly comprise α, β, or γ rays, consisting of helium nuclei, electrons or positrons, and photons, respectively [29]. As these rays can be understood as particles emitting from the radioactive materials, their penetration ability is different, as illustrated in **Figure 11**.

The α particles could be stopped by a sheet of paper, while β particles are blocked by an aluminate plate. These two radiation should be omitted in design consideration for their weak penetration ability, but γ radiation should pay more attention in protection design. The γ radiation has strong penetration ability that thick lead plate can just damp its intension, and it is the main cause of the devices damage.

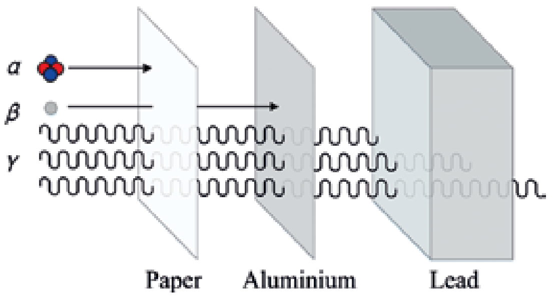

Figure 11. The penetration ability of α, β, and γ rays.

As γ radiation is a kind of electromagnetic wave, the radiation intensity is inversely proportional to the square of the distance. They are given in the following way

$$I_0^{'} = I_0 / L^2 \tag{1}$$

where I_0 is the intensity of the radioactive source, $I_0^{'}$ is the intensity at the measurement site, and L is the distance to radioactive source.

According to the Beer-Lambert law [30], the attenuation of γ radiation across solid materials is as follows:

$$\begin{cases} I = I_0 \cdot e^{-\mu t} \\ \mu = \mu_m \cdot \rho \end{cases} \tag{2}$$

where I_0 is the radiation intensity before passing through an object with the unit of Gy, I is the radiation intensity after passing through the object with the unit of Gy, μ is the linear attenuation coefficient with the unit of cm^{-1}, μ_m is the mass attenuation coefficient with the unit of g/cm^3, and t is the thickness of shielding material with the unit of cm.

5.2.2. Protection parameters of commonly used radiation-resistant materials

In the material attenuation formula above, the linear attenuation coefficient varies depending on the photon energy of the radiation source and the radiation protection material. Therefore, to determine the commonly used shielding material, linear attenuation coefficient is an indispensable part of the design process and will be presented in detail as follows.

According to Changsong [31], the mass attenuation coefficients, μ_m, of the same material are different at different photon energy levels. **Table 2** shows the mass attenuation coefficients for several common shielding materials at different gamma-ray energy levels.

As for the mass attenuation coefficients of the alloys or mixtures, they can be calculated according to the percentage of each element. Take tungsten-nickel-ferrum alloy (95W3.5Ni1.5Fe) as an example, the mass attenuation coefficient can be calculated through the following formula:

$$\mu_{m\_\text{alloy}} = 0.95 \times \mu_{m\_\text{W}} + 0.035 \times \mu_{m\_\text{Ni}} + 0.015 \times \mu_{m\_Fe} \tag{3}$$

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Radiation energy level/MeV	Mass attenuation coefficient μ_m (cm²/g)				
	Fe	Pb	W	Ni	U
0.1	0.368	5.52	4.39	0.439	1.89
0.5	0.0839	0.159	0.136	0.0868	0.194
1.0	0.0598	0.0703	0.0655	0.0615	0.0779
1.5	0.0487	0.0517	0.0498	0.0501	0.0549
2.0	0.0425	0.0453	0.0436	0.0437	0.0476

Table 2. Mass attenuation coefficients of commonly used shielding materials.

It can be found that the commonly used radioactive sources are Co^{60}, Cs^{137}, Ir^{192}, I^{131},etc. The specific data are shown in **Table 3**.

According to **Table 3**, the average energy of Co^{60} gamma ray is the highest among the commonly used radioisotope, which is up to 1.25 MeV. Considering the protective performance of the shielding material, it will weaken with the increase of γ-ray radiation energy. Therefore, the protection design of the robot is selected under the most demanding conditions, which is 1.25 MeV.

According to Taoyi [15], the commonly used shielding materials include tungsten, plumbum, uranium, and tungsten-nickel alloy.

By interpolating the mass attenuation coefficients at 1 and 1.5 MeV in **Table 3** and checking the corresponding density, the attenuation coefficient of each material at 1.25 MeV is obtained, as shown in **Table 3**.

5.2.3. Radiation shielding design of radiation-resistant robot

The radiation shielding design of robot is divided into two steps: first to analyze and determine the radiation sensitive electronic components and their corresponding positions. Then through comparison and calculation, one can finally determine the material and the corresponding thickness.

As discussed in Refs. [16–18], the radiation-sensitive components in robot mainly include electronic components located in the body and various sensors exposed to the environment. For the electronic components installed inside the robot, taking into account the overall protection

Radioactive source	Gamma ray energy	Half-life
Co^{60}	1.25 MeV(1.17 and 1.33 two channels)	5.27 y
Cs^{137}	0.662 MeV	33 y
Ir^{192}	0.4 MeV	74.2 d
I^{131}	0.364 MeV	8.02 y

Table 3. Radiation energy level of generic radioactive source.

of mobile platform and manipulator will greatly increase the weight of the robot, thus affecting its motion flexibility. So the radiation-resistant protection for internal components are achieved by the method of centralized method, namely the components are put together in a shielding box, while the method of separate protection is adopted for some scattered components. For the encoder, the controller and the drive, a shielding layer should be installed on the side of the vehicle body; for the external visual sensor, the shielding material is used for the overall coating, while the front of the CCD sensor is made of lead glass. Meanwhile, the shielding coating is applied to the inner wall of the vehicle body and the manipulator. The protection for vehicle body and the manipulator are shown in **Figure 12**.

After determining the protection position of each electrical component, the appropriate material and its thickness can be calculated and selected. According to the radiation lifetime test in Ref. [10], the electronic device can be divided into CCD sensor, motor and drive, laser ranging sensor, and other electronic devices. The cumulative dose of radiation that can be sustained by each kind of device is shown in **Table 4**.

Based on the attenuation law of gamma radiation through solid material, the cumulative radiation dose rate of different materials in different thicknesses in external environment can be obtained. Taking the normal working time of 3 h as the standard, the critical radiation dose rates of radiation-resistant materials in different thicknesses are calculated, just take the condition of 3 mm thickness as an example, illustrated in **Table 5**.

Finally, we need to balance the vehicle's weight and mobility, as well as the material's processing performance and radiation protection capability, and then the radiation protection material and its corresponding position can be determined. Meanwhile, the distance factor that the cumulative radiation dose of the vehicle is less than that of the manipulator should also be taken into account. After comprehensive consideration, the lead and high-lead glass are chosen as shielding materials, where the thicknesses for manipulator, vehicle, CCD front glass, visual sensor and laser ranging sensor are 10, 3, 8, 5, and 5 mm, respectively. The critical

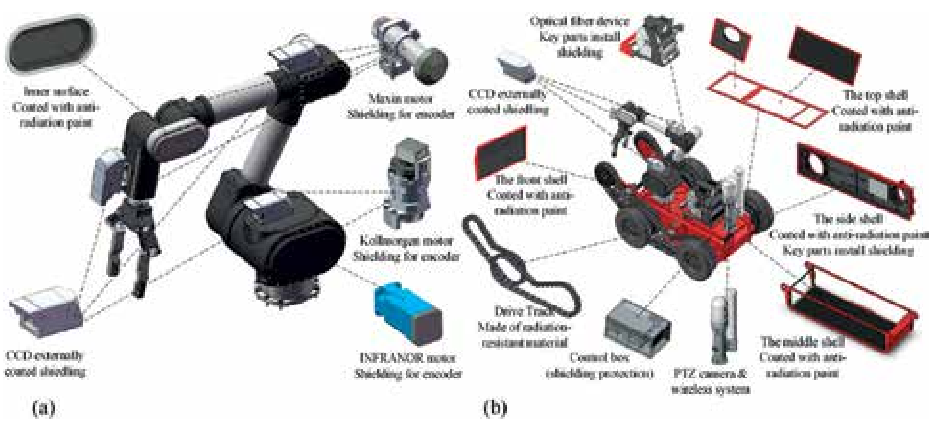

Figure 12. The radioactive shielding protection of the robot. (a) Radioactive shielding protection of maniulator, (b) radioactive shielding protection of track vehicle.

Electronic components	CCD camera	Motor diver boards	Laser scanner	Other components
Cumulative radiation dose	140 Gy(169 Gy)	140 Gy	124 Gy	200 Gy

Table 4. Cumulative radiation dose of various electronic devices.

ambient radiation intensity for each part to maintain normal operation for 3 h is shown in **Table 6**. Taking the attenuation of radioactive sources in the air into account, it is appropriate that the radiation resistance of vehicle and laser radar is weaker than that of motors.

5.2.4. Radiation-resistant technology of rubber components

After a certain amount of radiation dose, the rubber will be molecular bond breaking, degradation, or re-crosslinking. So, some of the robot components (such as tires, crawlers, and cables, etc.) need to be carefully considered during design. It has been proved in Ref. [15] that Ethylene Propylene Diene Monomer (EPDM) has good resistance to aging and radiation. By adding a radiation-resistant agent (Bi_2O_3), its anti-fatigue strength and radiation resistance will be further strengthened. Such a material will be used for robot's rubber components.

As for the cable in the wired communication system, the semiflexible/semirigid coaxial cable is chosen with the radiation resistance more than 10^6 Gy, and can be used for a long time working at the temperature range of −100 to +150°C. The cable can be used for signal transmission, comprising inner conductor, insulating layer, outer conductor, and sheath layer.

5.3. Irradiation test for electronic components

The following will describe the specific process of irradiation experiment according to Nagatani [16]. The electronic components for the irradiation experiment include a CPU board, a motor with an encoder, a motor driver board, a wave power transfer device, a visual CCD sensor, and a laser radar. The test is intended to use three linear Co^{60} as radiation sources. For safety, we place the radiation source in an underground cooling pool. When the experiment begins, raise the radiation source to the center of the shield test area to radiate the surrounding objects. The cumulative irradiation of the target can be adjusted by the distance to the radiation source. Theoretically, the radiation intensity decreases with the square of the distance. In the Japanese irradiation experiment, the radiation intensity of the γ source at 0.66 and 0.45 m from the radiation source are 20 and 40 Gy/h. More details will be discussed below, and the experimental device and space layout are shown in **Figure 13**.

Shielding material	Wolfram (Gy/h)	Plumbum (Gy/h)	Uranium (Gy/h)	W-Ni-Fe alloy (Gy/h)
CCD camera	65.21	57.43	68.07	63.66
Motor diver boards	65.21	57.43	68.07	63.66
Laser scanner	57.76	50.87	60.29	56.38
Electronic components	93.16	82.04	97.24	90.94

Table 5. External radiation intensity of electronic components (t = 3 mm).

Devices	External cumulative dose rate (3 h)
CCD camera	59.45 Gy/h (front) and 65.95 Gy/h (around)
Laser scanner	58.41 Gy/h
Motor diver boards	93.20 Gy/h
Electronic components (CPU board, POE devices, etc.)	82.04 Gy/h

Table 6. Critical radiation intensity after protection.

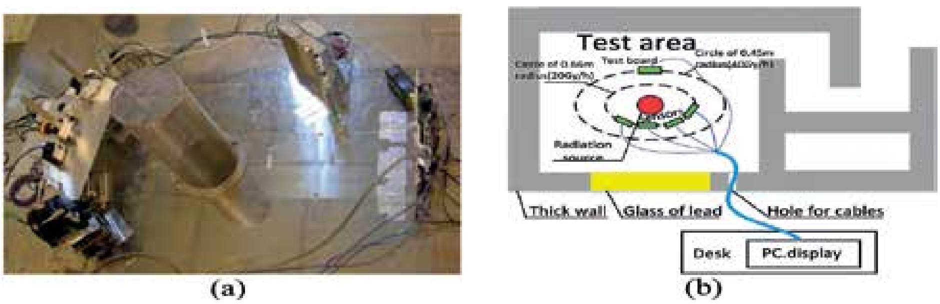

Figure 13. The test devices and spatial layout of irradiation tests. (a) Device configuration for the irradiation test, (b) layout of devices and experimental facility.

1. Restarting tests of computer motherboard: As shown in **Figure 13**, the computer motherboard is located at the distance of 0.6 mm from the radiation source. Considering the motherboard can still work after the flash card is destroyed (the flash card is mainly used for computer system startup function), we need to restart the computer every 30 min to confirm whether the flash card is failure.

2. Tests of sensors: Sensors are placed at the distance of 0.45 m from the radiation source. The CCD, laser radar, and photoelectric switch are connected to the monitoring computer via the LAN. The measurement results of sensors are obtained by an external monitoring computer, and the times of abnormal and complete failure of the image are recorded.

3. Tests of motor drivers: The motor driver is placed at the distance of 0.45 m from the radiation source, and connected to the monitoring computer via Controller Area Network (CAN) bus by continuing to send virtual commands to detect whether it fails. The motor can be considered to be placed outside the irradiation room to the effectiveness of the driver.

By recording the experimental results, we can find that the radiation resistance data are similar to the results of Ref. [10] and also prove the correctness of the previous subsection theory.

6. Fire-fighting robot

The conflagration accident is another typical hazardous condition, which is dangerous and hostile to rescuers. This dangerous environment is filled with thick smoke and high temperature,

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as well as flames everywhere. In consideration of these challenges, two approaches are utilized to cope with the hostile situation: (1) waterproof and dustproof design is dispensable as the debris and water in the fire site and (2) high temperature resistance design is also necessary for the robot inside components protection.

The fire rescue robot is shown in **Figure 14**, comprising main body, high-pressure sprinkler and control box. The track system includes flame retardant rubber externally and metal skeleton internally, ensuing the walking ability and stability even in the worst condition that the rubber melts for high temperature. Additionally, the autonomous cooling sprayer is also integrated to ensure the normal work in the high temperature.

6.1. Temperature protection and waterproof design of fire-fighting robot

As the temperature in the field of flame can reach up to 700°C, and nearly everything will be melt. Hence, the high temperature resistant ability should be discussed and conceived. Moreover, the cool water is inevitably sprinkled on the robot, and the waterproof technology is also needed.

6.1.1. Temperature resistance design of fire-fighting robot

The temperature resistance design is implemented through the autonomous cooling sprayer, which can spray cooling water on the whole body of the fire-fighting robot. This approach has two advantages: (1) the high-pressure water cannon is the essential tool for fire controlling; the autonomous cooling system is just an additional application of the drainage system and (2) other approaches for temperature resistance, such as the thermal insulation, will increase the design difficulty and the overall weight of the robot, reducing the traffic-ability and crossing ability. So the autonomous cooling sprayer may be the best selection.

6.1.2. Waterproof design of fire-fighting robot

In order to satisfy the requirements of waterproof and dustproof sealing performance, protection grade of the robot must reach IP67. The mechanical design comprises of two methods: the static sealing method and dynamic sealing method, which is similar to the waterproof implementation of coal mine robot (as illustrated in part 3.1.3). The specific implementation details will be omitted.

Figure 14. The fire-fighting robot and tests.

6.2. Fire-fighting robot environment tests

In order to test whether the fire-fighting robot can meet the requirements in the fire environment, Tangshan fire-fighting robot was utilized in the Imperial Palace Museum (shown in **Figure 14**) and other places for fire drills to testifying the validation of this robot and the protection technology.

The first fire drill was held in the oil storage tank domain, assuming the fire broke out suddenly and the fire had been out of control. As the fire had been out of control, temperature nearby was rather high which was possible for rescuers to get close. Three fire-fighting robots rushed into the core field of fire under the operators' commands, and the fire was under control quickly, as shown in **Figure 15**.

Figure 15. The high temperature protection tests of the fire-fighting robot.

7. Conclusions and future work

In this chapter, protection technologies for four kinds of rescue track robots are discussed and presented to assist the CBRNE emergency. The specific protection technology for the four track robots is listed as follows: (1) The coal mine robot is modified by mechanical shielding, components reposition, and electronic protection, getting a good performance for explosion-proof and waterproof. (2) Biochemical sampling robot realizes its protection technology through a 6-DOF manipulator and several sampling instruments, as well as the waterproof design against decontamination. (3) Radiation-resistant robot completes the radiation shielding design and rubber components selection, satisfying the requirements of working well in the radioactive environment. (4) The fire-fighting robot adopts the high temperature resistant design and waterproof technology to ensure the robot can work in high temperature environment.

The future works may focus on the followings: as the diversity and distinction of hazardous conditions, we need to dig more deeply into requirements and protection methods of different hazardous environment. In addition, the tradeoff between the protection level and other performance of the robot should be optimized and considered, such as balancing the trafficability and radiation-resistant ability in the radiation-resistant design process or the types of sampling tools and dimension of the track-vehicle.

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Section 5

Occupational Health and Safety Issues in Robot Operations

Chapter 5

Safety Assessment Strategy for Collaborative Robot Installations

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Additional information is available at the end of the chapter

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Abstract

Industrial resource efficiency can be improved if the safety barrier between humans and robots is removed, as this enables operators and robots to work side by side or in direct collaboration to solve a task, usually referred to as a collaborative robot installation. Even though technology development makes the barrier removal ever more feasible from a safety perspective, this still produces a possible hazardous working environment, and safety assessment strategies are crucial. A wide area of knowledge is required to assess all fields that can help ensure safe human-machine interaction. Here the focus is primarily on providing a description of the key fields identified, including how operators psychologically accept working with robots, and providing a cursory description of the research front for each individual field. In addition to covering a large number of parameters, the assessment strategy also needs to be cost-effective. A significant part of all parameters that can be considered when attempting to produce optimized and cost-effective collaborative robot installations will also have a direct impact on operator safety. Hence, assessments for safety, and assessments for cost-effectiveness, cannot be separated, and are treated as two objectives that need to be viewed in sync.

Keywords: collaborative robots, productivity, safety, strategy

1. Introduction

Automation and robots are expected to have a major impact on the society in the coming years, and it has been said that about 47% of USA's current jobs will be automated within 20 years [1]. A study from MIT [2] argues, however, that one should not analyse what are the professions that can be automated, but instead the tasks that can be automated within each profession. The MIT authors write that a very large proportion of all professions includes elements that can be automated and assume that the automation of the society will be slower, but that a large part of all work will be carried out in close collaboration between people and machines. A study from 2015 by the Boston Consulting Group [3] argues for a similar development.

Humans have to some extent always worked to create solutions that can enable more efficient collaboration between people, tools and machinery in order to deliver value that is increasingly cost-effective. This work is today more important than ever for several reasons:

- Industrial customers increasingly demand that maximum value will be provided, before taking industrial business decisions.
- Competition between companies that can supply industrial value is increasing more and more, which places greater demands on optimizing the utilization of all available resources, which in turn places greater demands on effective interaction between man and machine.
- The Industry 4.0 concept puts people at the centre of industrial activity and industrial development. The concept has been of great importance for a large part of the ongoing industrial development. The view of mechanization and automation as a way to increase human capacity, and not a way to replace humans, has been a major theme in industrial thinking. Methods to ensure effective collaboration between man and machine are therefore increasingly in demand.
- It is not yet possible to cost-effectively automate all production to 100%, and working methods that can take maximum advantage of humans' and robots' respective strengths are thus of greater value to the industry.

All industrial assessment strategies must be an integral part of the above trends and they must, with ever greater clarity, continuously guarantee answers to the questions: What value do I want to deliver through the coordinated use of all available resources? And, how can I take advantage of technological advances to deliver ever more value, ever more resource efficient?

One approach to increase industrial resource efficiency is to remove barriers between robots and operators, enabling them to work in direct collaboration and take full advantage of their respective strengths, such as human abilities for adaptation and robots' speed and precision, to solve a task. Technology development within several fields such as sensors, control technology and programming has also made it ever more feasible to remove barriers from an operator safety perspective. However, even though technology development continuously makes it more feasible to remove safety barriers, robot installations without these barriers still pose hazardous working conditions for operators in several ways. In addition to possible psychological distress when working in absolute proximity with robots, there are several physical hazards such as risk for crushing, impact and puncture wounds. Furthermore, one important objective with collaborative robot installations is to reduce ergonomic problems. However, methods to verify that installations also actually reduce ergonomic problems are still required. Advanced and reliable robot control is vital to avoid physical injury, and as functions for robot control are increasingly moving to the "cloud", this means that lacking IT-security also directly results in operator safety hazards.

Collaborative robot installations can today be found in several application areas such as service robots and industrial robots, mainly deployed for assembly tasks. This chapter focuses on industrial collaborative robots in a production system. The safety assessment strategy for collaborative robots is an attempt to give a guided tour: How to identify the areas that should be considered and developed to ensure that all types of collaboration installations can be assessed from a safety and operator acceptance perspective, as well as from a cost-effectiveness perspective. And, how to make safety assessments in different phases of the development process, such as the pre-study phase, installation phase or operational phase.

Questions concerning the interaction and collaboration between people and machines affect a wide area of knowledge and include technological and methodological, as well as psychological and physical aspects. To catch all the areas that can be processed and further developed to increase the success of safe collaborative robots is in other words a challenge in itself. The method used to identify areas to be assessed is utilization of experiences from the two ongoing Swedish collaborative robot projects: The project "Team of Man and Machine" (ToMM) and the project "A Safety Model for Collaborative Robots" (SCOR) financed by the Swedish innovation agency (Vinnova) where larger collaborative robots are studied. The analysis is based on the existing safety Machinery Directive standards[1], ISO10218[2] and the ISO/TS 15066[3] that support installation of collaborative robot solutions. The analysis is also based on a selection of articles that discuss collaborative robot challenges, to a large extent based on earlier documented works resulting from the ToMM project, including a safety assessment process developed for the ToMM project [4].

1.1. Definition of a collaborative robot

The standard ISO10218 defines four types of collaborative robots:

- Safety-rated monitored stop.
- Hand-guided.
- Speed and separation monitoring.
- Power- and force-limited.

These four definitions illustrate methods to manage safety issues and potential conflicts between different types of passive and active control instructions. However, they provide limited guidance on how to divide definitions of collaborative robots into segments that can make the assessment strategy development simpler to manage. A split into different conceptual layouts, small and large collaborative robots and standard and custom-designed robots may provide better guidance.

[1]http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006L0042&rid=6.
[2]https://www.iso.org/standard/51330.html.
[3]https://www.iso.org/standard/62996.html.

Three main types of conceptual layouts for collaborative robot installations have been suggested [5]:

1. The robot placed inside safety fences with the workpiece placed between the robot and the operator. The collaboration is performed with the workpiece acting as a safety fence, making it possible for the operator and the robot working together on the same task.
2. The operator and the robot share the same workspace on the same side of a workpiece. Here, the ISO/TS 15066 guides on how to solve the safety issues through regulation of robot arm speed. This layout can be arranged in several ways, and sensors are demanded to control the robot arm speed.
3. The operator and the robot are working side by side, but do not work on the same workpiece at the same time. Here, the operator can either prepare for the robotic operation or vice versa. The workflow will have a character similar to a line flow instead of a collaborative task.

Large robots could be defined as the robot size required to lift and manipulate components that would otherwise require a lifting tool, or that have greater reach than humans. To optimize installations of large robots with regard to safety and productivity, it requires more analysis than to optimize installations of small robots, as the installations of the larger robots affect the need for lifting tools, the need to analyse component logistics solutions, layout design and level of automation of the installation.

Small robots could be defined as the size of the robots which is required when components are not large enough to require a lifting tool that otherwise would be needed as an alternative, and that has a range similar to a human. The boundaries as robots move from being "small" to becoming "large" are of course not distinct.

Another division can be made between standard robots and robots that have been custom-designed for collaboration. The probable difference is that the custom-designed robots have "guaranteed" technological abilities to provide adequate response to various physical control instructions from operators. Examples can be hand-guided programming capacity, sensors in the moving parts, power steering, safety design and so on. As with the boundaries for large and small robots, the boundaries of where a robot moves from being a standard robot to be custom-designed are indistinct.

1.2. Adjacent technology fields

There are several technologies that are adjacent to the area of collaborative robots. Consideration of these can illustrate issues that could be seen as peripheral but which may also be of great importance for the development of safe collaborative robots, and should be mentioned.

Automatic vehicles carrying people can come in situations where they are faced with the choice whether to protect the passenger or the people that appear in front of the vehicle [6]. It is

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not impossible to imagine situations where industrial installations need to be programmed to make similar choices on *whom* to guarantee safety.

Challenges when developing exoskeletons, telerobotics solutions, for example for medical surgeries, and some computer games have several questions in common with the development of collaborative robot installations. Such is the question of what power response should come from the machine as a response to human force.

With such divisions it may be possible to section the analyses of collaborative robots with respect to general and specific safety issues.

1.3. Collaborative robots mean new challenges

As enhanced and safe collaboration between people, tools and machines always have been sought after, it is relevant to ask what challenges are really new for collaborative robots.

Two main methods are currently used to manage safe and effective interaction between man and machine with moving parts:

- Ensuring a clear separation of different types of control instructions (such as programmed instructions to a robot or physical control instructions to, e.g., a chainsaw) so that the machines do not receive conflicting instructions.
- Ensuring clear, often physical, barriers between man and machine, such as fencing around a robot or protective equipment for chainsaw operators, supplemented by regulations and user manuals.

The need to have these barriers and distinctions of control instructions is, however, ever more reduced as technology is developing:

- Cheaper and better sensors and control technology make it increasingly possible for robots to become aware of their surroundings.
- Improved human-machine interfaces make it easier both for the operators to predict robot movements and for the robots to take on physical operator instructions.
- Better sensors and interfaces also allow for several methods of control, such as power steering and hand-guiding, voice instructions or sign instructions, combined with programmed instructions.

Taking these developments together, the need for older types of powerful barriers, for example in the form of cages for equipment with moving parts, is continuously decreasing. The possibilities to take advantage of several different types of control instructions that can be given simultaneously are increasing.

The technical challenges that can be considered new for collaborative robots can thus be said to be mainly how to design safety and control systems where there are several parallel-operating sources of control instructions and where the last safety barrier consists of the surface of the moving robot arm.

2. Analysis of a collaborative solution: value and optimization

In a world of increasing competition, it is becoming increasingly inadequate to focus on improving individual parameters, such as reduced need for manual hours, and use these parameters as the basis for business decisions, for example automation decisions. Demands are increasing instead of carrying out a more comprehensive overall assessment of all parameters that are affected by a business decision. This is especially important in analyses aimed at identifying whether collaboration solutions are conceivable alternative production measures, given the large number of parameters that affect/are affected by such a technical solution and the complex relationships that exist between these parameters. This makes it relevant to highlight the need for advanced means of value analysis and optimization of the layout and operation as a success factor for this type of production, where safety is an integral part of "success". Such an approach should include a number of elements:

- The desired overarching value of an installation must be described, for example a total reduction of production costs, over an appropriate time frame, where all production costs are included, such as the cost of changing production settings, manual labour, service, upgrades and so on.
- Identification of internal connections between the changes in certain parameters, such as selection of "humane" colour and surface layer of the robot, and the impact these selections have on other parameters, such as increased acceptance by operators working in the vicinity of the robot.
- The relationship between all the inputs that affect the productivity and safety of a collaborative robot installation and the desired overall value of the installation must be identified.
- An optimization routine to find the combination of input parameters that provide the best ratio output/input must be developed.

The analysis also needs to allow for an evaluation of a collaboration solution in relation to alternative production measures. It requires both an account of all the parameters that should be considered when evaluating a standard automation decision and new/more complex influencing parameters that are relevant for collaborative installations.

Some first steps have been made in the development of such a model in the Vinnova project "Lean Automation Development" (LEAD) and the results are reported in the "Lean Automation Handbook" [7].

3. General model for safety assessment

A fundamental challenge for collaborative robot success is indeed how adequate safety can be guaranteed in a cost-effective manner. As mentioned, safety is a major challenge for several reasons: powerful barriers between man and machine cannot be utilized, the different types of injuries that can occur to various parts of the body have different pain thresholds, and safety is dependent both on the technology and on operator actions. In addition, the safety handling needs to be in accordance with existing regulations and, not the least, be cost-effective enough to enable a commercial deployment of collaborative robots as a solution to industry's productivity challenges.

A general assessment model for dealing with safety issues for collaborative robots must therefore fulfil four conditions:

- It needs to comply with laws and industrial regulations.
- It needs to consider all safety-influencing factors and ensure the right safety for people, property and the environment.
- It needs to ensure sufficient operator acceptance.
- And, it must be sufficiently cost-effective to make interacting robots commercially interesting.

3.1. Existing legal standards and safety routines

ISO 10218:2011 is a two-part document. Part 1, entitled "Safety of Robots", is intended to be fully compliant with the European Machinery Directive. Part 2 on "Safety of Robot Integration" is intended to address workplace safety requirements and is directed more to the end-user than the manufacturer. In addition, new modes of operation are allowed: "synchronized" robot control, "mobile" robots mounted on automated guided vehicles (AGVs) and "assisting" robots working in a "collaborative workspace" with robot users. ISO 10218 is developed based on ANSI RIA R15.06-1999 and is a revised safety standard for industrial robots. One of the updates is on safety-rated soft axis and space-limiting, which is the enabling technology for the other collaborative robot operation. The safety-rated soft axis and space-limiting allow positive control of the robot location and thus the safety for the robot users. The case when robots and humans have to share an immersive operational space, however, is not clearly discussed in ISO 10218:2011. It suggests human-robot segregation in the workplace as the way to obtain safety. ANSI RIA R15.06-2012 is a revised version of R15.06-1999, harmonized with ISO 10218:2011. Technical Specification TS 15066 (Robots and Robotic Devices–Collaborative Robots)[4] specifies safety requirements for collaborative industrial robot systems and the work environment, and supplements the requirements and guidance on collaborative industrial robot operation given in ISO 10218 -1 and ISO 10218-2.

Existing robotic safety systems comprise only fixed detection zones and do not facilitate direct human-robot interaction at close distance and in immersive environment. Additional safety practices when operators are working in direct contact with robots must therefore be developed. TC 299 "Robots and robotic devices", which was formed in June 2016, is an initiative that in the future will bundle all standardization related to industrial and service robots. Work group 3 within the TC 299 is currently working on a technical report on the safety of manual load stations, that is stations where a worker hands over a part directly to a robot end

[4]https://www.iso.org/standard/62996.html.

effector (e.g. a gripper)[5]. This will take the regulatory safety framework closer to covering all situations where operators work in direct contact with robots.

3.2. Safety when operators work in direct robot contact

Utilization of insights from several different research areas can contribute in various ways to achieve sufficient and cost-effective safety when operators are working in direct contact with robots. Below is a list of such identified areas, to some extent recollected from an earlier work [8] including the already mentioned issues of communication through several parallel communication channels. The list includes considerations and measures that can be taken in order to make the safety assessment reasonably comprehensive, covering several types of robots, applications and the conditions that are relatively unique for collaborative robot installations.

- A picture must be created of what appropriate safety means when the operator is working in direct contact with a robot, which should include all kinds of safety issues and damages that may arise: pinching, impact, cutting and so on. Different thresholds of injury/pain/force to various parts of the body means, as mentioned, challenges for cost-effective risk assessment.
- The safety analysis should also take into account musculoskeletal disorders and ergonomics from different perspectives: the design of individual workplaces, the tasks to be performed, holistic perspective on production flow (system level) and the organization of work [9]. If working environment conditions are not taken into account when companies are taking production effciency measures, employees can be adversely affected [10]. Ergonomic risk factors and assessments of working conditions need to be considered. This includes focus areas such as physical exposure/load variation (physical), demands, control, communication and work organizational aspects.
- The system level that machine suppliers use when giving guarantees must be identified. Safety issues related to interfaces to supplementary technical systems that integrators use to create effective collaborative production cells must be considered.
- It must be taken into account that different robots have different technological capability to respond to operator instructions and sensor information.
- One has to deal with the fact that robots in collaborative installations must comply with at least two different, potentially conflicting sets of instructions; programmed instructions and physical, passive or active, instructions from the operator.
- One must also deal with the fact that delivery of the physical instructions from operators to robots may take place through multiple communication channels as force, voice, signs and so on. All these instructions can be conflicting and pose a potential risk factor.
- The division of roles between the robot and the operator who determines what an actor needs and must do must be designed in a way that supports safe operations [11]. Game theory [12, 13] and optimization [14] have been mentioned as ways to approach the problem.

[5]https://eu-robotics.net/cms/upload/downloads/newsletters/ISO-Standardisation-Newsletter_2016-04.pdf.

- Models to utilize existing and future technologies to detect the position of humans and their body parts must be developed. This includes systems that give the operator an indication of a robot's intentions and vice versa.
- Safety assessments must take into account a wide range of different applications and components to be handled by robots and operators, where some components are sharp while others may be soft.
- As more and more IT-related operations are transferred to the "cloud", operator safety increasingly also means the same thing as IT security.
- Regardless of the theoretical high-safety level, a collaborative installation must be designed so that operators feel it is acceptable to work in the immediate vicinity of a robot.
- As the robot's moving parts are the last safety barrier, there must be damage-minimizing solutions to handle a situation where a robot arm hits an operator, for example in the form of soft surfaces [15] or airbags.
- Ethical considerations where the priority of the welfare of different human actors may be necessary.

3.3. Further notes on cost-effectiveness

For a commercial operation, solutions for operator safety are of limited value unless this can be achieved in a cost-effective manner, that is to operate the installation in an economically competitive way. One measure to ensure this is to identify the cost-effective distribution of resources when considering a wide range of parameters that affect safety, mentioned earlier. Another measure to ensure cost-effectiveness is to integrate the safety assessment into the activities a company already is carrying out and allow the assessment to be an integral part of decision-making that must always be present before business decisions. Achieving such integral solutions should answer a number of questions to cover all steps companies commonly take before and after business decisions. How can:

- Existing overall company safety assessment strategies be supplemented so that these include assessment of collaborative robot solutions?
- The assessment be integrated in pilot studies to get a first indication of whether a collaborative installation can be a competitive solution?
- The assessment be integrated when developing requirement specifications, where the interface between the operator and collaborative robot is included?
- The assessment strategy benefit a machine supplier/Integrator need for safety assessment tools?
- The strategy take advantage of existing experience on how to ensure operator acceptance of working with powerful machines?
- The strategy be used during the installation and reconfiguration phases?
- The strategy be used during operation?

An important step when developing an assessment strategy is thus to identify how a company's current safety practices look like and what limitations they have to also ensure effective safety assessment considerations for collaborative installations.

4. Empirical insights and questions in focus

The following is a deeper discussion on some selected specific challenges for collaborative robots where the solutions may be particularly important for cost-effective safety.

4.1. Man-machine communication

Developing effective methods for the communication between operators and robots will be critical for productivity as well as safety. One important goal for a communication solution should be to arrive at a shared understanding between operator and robot. This indicates that using the simplified definition of communication, an act to convey intended meaning from one individual or entity to another, will lead to unsatisfying results, as it does not have the perspective of shared understanding. Instead, communication should be defined as an act or process that involves several modalities, to maximize possibilities for a shared understanding.

The physical control and communication must be intuitive and easy. In the long run, this means that communication models should be developed which are able to utilize the full range of communication channels people use, which includes detection, voice, sign language, force and touch.

The human-machine voice communication field is rapidly progressing. But it has not reached such a level that it is used to any significant extent for robot communication.

Detection can be viewed as a type of communication, where the robot's operation is affected (being stopped or slowed down) depending on detection of potentially hazardous positions of operators. Several detection systems are available. 3D vision systems, such as SafetyEye[6] from Pilz, that monitor the Cartesian space around robots and stop operations in case of danger via external sensors are promising. Pilz stereovision system has been accepted for worker detection in the robotics safety area based on human-robot segregation in different zones. 3D-camera technology based on time-of-flight (TOF) measurement, such as Microsoft Kinect[7] sensors, has also been tested with promising results for safety in human interaction with robots. Ultrasound detection of humans is another method that has shown promising results[8].

Some writers highlight sign communication as a desirable method of physical communication [16]. As gestures are culturally bound [17] it could be assumed that methods to compensate for this must be developed to make this communication method universally effective.

Of the physical control methods, using physical force when hand-guiding, and as a stop

[6] http://www.pilz.de/products/sensors/camera/f/safetyeye/index.en.jsp, 2009.
[7] http://www.xbox.com/kinect.
[8] https://www.technologyreview.com/s/603720/home-assistants-like-amazon-echo-could-be-a-boon-for-assisted-living/?set=603749.

signal when the robot comes in contact with a human, is the most common. Hand-guiding of small robots works effectively as a programming method. But the hand-guiding of larger robots in which they are used to lift heavier components involves an element of risk, for example pinching, when the heavy component is to be mounted. The ToMM project has solved this by using an "enabling device" (handles on the gripper in the middle of **Figure 1**). This solution, however, reduces productivity as the operators cannot, with their hands, hold or manipulate the component the robot is holding in its grippers, and other solutions would benefit productivity. During physical collaboration where there is a direct contact between cooperating people, an important part of communication is carried out through a combination of touch and physical force. Blue Danube Robotics' AirSkin solution is a safety sensor solution that covers the entire surface of the robot with a soft, tactile skin[9]. This points towards a future where efficient control and communication solutions is based on the use of smart textiles, on the robot as well as on the operator, as a communication and control tool between the operator and the robot. Smart textiles also have the potential to add more "senses" than people have, such as magnetic "senses", gyros and ability to automatically document events. Smart textile gloves and clothing have the potential to act in several parallel tool roles simultaneously, such as sensors, actuators, safety barrier and registrars.

Advanced prosthetics also points towards a future of highly intuitive and flexible collaboration, where robots may be considered an "extension" of a human operator. Thought control of prosthetics has not only proved possible, but also has advanced to the level where individual

Figure 1. Enabling device for hand-guiding, the ToMM project (handles on the gripper).

[9]http://www.bluedanuberobotics.com/?page_id=87.

fingers can be moved using thoughts only [18]. There is limited reason to believe that this trend will not continue towards a future where all machines that require human instruction, not only prostheses, will be the subject of studies of mind control. One study from MIT[10] and one from Brown University[11] have already shown that an operator can give feedback to correct collaborative robot mistakes, using thoughts only.

4.2. Acceptance and perception

Technical system development could either be driven by technology or by human/user needs, and user-driven technical system development needs to take psychological aspects into consideration.

Technical system capacity is essential for safety as well as productivity of collaborative robot installations, but is not sufficient. If operators' perception of the robot system does not lead them to feel safe in the workplace, the adoption rate of these types of installations will be slower compared to a situation where operators feel comfortable or even enjoy being in the presence of robots. Perception and solutions for general acceptance also have wider implications as autonomous and robotic solutions reach ever more areas in the society. As mentioned, it has for example been shown that if it comes to situations where safety for a group of people only can be guaranteed for some of the people in the group, it will be challenging to decide which part to protect, as different groups of people have strong, and differing opinions regarding this decision [6].

Perception is also interlinked with cognition and culture, and how robots are perceived goes hand in hand with the understanding of robots in the society. Even though many share a fascination for robots, it is not uncommon that there is also a reluctance to accept robots. Possible job losses due to robotization and fear of possible "robot take over" as a consequence of advanced Artificial Intelligence may be reasons for low robot acceptance. In order to overcome this possible reluctance, inspiration could be found from technical solutions within the rapidly progressing social robotics field. The solutions deployed to increase the use of robotics in healthcare may also be used to influence and change the attitude to robots as something threatening.

Perception can itself be considered a form of communication, where operators' perception of the robot and the robot's ability to interpret body language and intentions are likely to have significant relevance for productivity. For example, gaze cues [19] have been discussed as a form of communication. A collaboration solution that has not been balanced, where the operator does not feel to be in control but is forced to wait for or is startled by the robot, will also reduce the acceptability.

There is a close relation between how individuals experience and interpret objects and what names these individuals use for the same objects. One way to increase acceptance is not using the word "robot", but instead other words such as "assistant" or "tool" [20]. Another is to work on the robot appearance, and use developed tools to measure the acceptability [21]. The

[10]http://groups.csail.mit.edu/drl/wiki/images/e/ec/Correcting_Robot_Mistakes_in_Real_Time_Using_EEG_Signals.pdf.
[11]http://h2r.cs.brown.edu/

actual operation of the robot also affects the acceptability and it has been shown that the correlation between for example false alarms and acceptance [22] and methods to measure the level of trust has also been developed [23]. Further development of methods to create greater acceptance can, however, be assumed to be an important future research objective.

4.3. Layout for production cells and production lines

Designing an efficient layout is important for all production cells. For small collaborative robots, the choice of layout is, relatively speaking, a minor challenge. An important reason for this is that small collaborative robots often can be inserted into an existing production flow for unloading of simpler assembly work.

However, experience from the ToMM project shows that optimization of the production cell layout is a significant challenge when working with large collaborative robots. There are several reasons for this. Choice of automation level and location of the transfer point between the autonomous and collaborative/hand-guided robot operation must be made. Several methods on how to carry out the transfer can also be used [24]. Solutions that take advantage of the opportunities for effective component logistics must be developed. And, all the various alternative designs must always be evaluated with respect to safety. In the long run, safety solutions for installations with multiple interacting robots and operators in the same cell must also be developed.

Design solutions for assembly lines that is in continuous motion will mean additional challenges, which is about to be studied in an upcoming sub-project of ToMM.

An important tool is here solutions for simulation of assembly cells and assembly lines where the machines as well as human behaviour can be simulated [25, 26].

4.4. Set-up, flexibility, programming and learning

Set-up time has in some cases been shown to be reduced to as little as 1 hour when small collaborative robots have been installed in existing production flows [27]. Experience from for example the ToMM project has shown that the set-up times for large collaborative robots can be much longer, though.

Choosing an optimized and safe layout can indeed be resource demanding. Programming also requires significant resources, if the hand-guiding programming method cannot be used. This part of the installation can be even more resource-intensive than the programming for fully automated assembly cells. The reason for this is that it requires a programming block with "standard programming" for the workspace in which the robot operates autonomously, plus a programming block for the workspace in which the collaboration is carried out. Finding solutions for optimized, safe and rapid set-up is an important objective for large collaborative robot developers.

Ensuring that more productive technology is utilized in actual production when such technology is available is always important. Efficient work models for this are particularly important for collaborative robots as productivity improvements can result from at least two types of technology utilization.

One type of utilization of new technology is the introduction of more productive technology systems, for example human detection, communication, control and so on, as this new technology becomes available for practical use.

Another type of technology utilization for continuous improvement of productivity is to use learning tools. One important reason to use collaborative robot installations is that humans are better at certain things. However, recognizing this leads to the question whether robots can learn from humans working in existing collaborative installations. This is also indeed "a very active area of research", according to Ken Goldberg, professor at the University of California, Berkeley, specializing in machine learning and robotics. It has been reported that "a Canadian start-up called Kindred AI is teaching robots how to perform difficult dexterous tasks at superhuman speeds by pairing them with human "pilots". When a robot struggles, it asks for human help and is then controlled via VR—but the robot keeps close watch, making use of reinforcement learning to ensure that it can perform a similar task in the future"[12]. The result of this is that robots can be taught to finish jobs using only half the time humans need for the same job. Goldberg says that "It's at the core of what I believe is a big opportunity in robotics. There's a huge benefit to having human demonstration".[13]

"Deep learning" is another learning strategy, which also has shown to improve productivity of collaborative robots.[14]

5. Long-term safety vision

The foregoing sections have reasoned around different areas that are important for the commercial success of safe collaborative robots, practical experience from such installations, the future development steps that are needed and those that are to be expected. The following is a brief discussion of the possible end of the road for safety assessment strategy development. This can be relevant as a guide for long-term focus of developmental resources.

The work in today's industrial production and other corporate activities takes place on a scale from 100% manually by human operators, to 100% automated. In all cases where operators interact with any kind of machine with moving parts, there must be some form of communication between man and machine, and some form of barrier between man and machine to minimize the risk of injury, should all communication methods fail. The vision for how this communication method and barrier should function can be said to include four main areas:

- It must enable an intuitive and frictionless interaction between robots and humans. This interaction should at least function in a similar way as when people help each other to lift and manipulate objects, and in those situations use all of the communication methods available to make the joint manipulation efficient. If one takes this to its logical conclusion, the vision

[12]https://www.technologyreview.com/s/603745/how-a-human-machine-mind-meld-could-make-robots-smarter/ reinforced learning.
[13]https://www.technologyreview.com/s/603745/how-a-human-machine-mind-meld-could-make-robots-smarter/ reinforced learning.
[14]http://blog.robotiq.com/machine-learning-robots-can-now-learn-stuff.

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is also that people should be able to communicate with robots directly from their thoughts, which earlier research in advanced prosthetics, and now also research on collaborative robots, have shown is fully possible.

- The above should also support a method for intuitive and safe distribution of roles between man and machine, including a regulatory framework for the initiatives robots can and must take, and how they should respond to human initiatives and commands.
- The solution should be able to take full advantage of opportunities to record, document and act on positions and events, for example through a well-developed regulatory framework that governs the registration, documentation and action.
- The safety shall be fully integrated into the machine to enable direct use of collaborative robots both in production and in development, *without* the requirement of safety assessments.

In addition, it should not be resource-demanding to identify when a collaborative robot installation is the most cost-effective solution to an industrial problem. This is of fundamental importance as technological developments make both collaborative robotic solutions and technological alternatives increasingly competitive, at the same time. Beyond the fact that the front of what can be cost-effectively automated to 100% quickly moves forward, new production techniques such as 3D printing reduce the need for bonding, assembly and so on. As shown in the European Union roadmap for precision assembly [28], miniaturization and increased complexity of components and equipment make manual assembly possibilities ever more difficult. This increasingly requires 100% automation. The process where more and more hardware is converted to software also reduces assembly needs.

A safety assessment strategy for collaborative robots must therefore be seen in the light of both trends that increase the possibilities to realize and utilize collaborative robots efficiently, and trends that make industrial collaborative robots less relevant. Such a strategy for collaborative robots thus must be used as a dynamic tool that continuously needs to be checked against all influencing developments. It is reasonable to assume that there are different time windows for different applications where it is relevant to focus on competitive solutions for physical interaction with the robots, which justifies a development of a safety assessment strategy. When these windows shut, it can be assumed that robot installations, or other new technology, with a 100% degree of automation become the most competitive robot solution. At the same time, one can assume that the IT development continually will open new time windows for intimate interaction between man and machine at increasingly higher cognitive levels. Possibly, or maybe hopefully, the time window for the highest cognitive level never closes.

6. Conclusion

Installations of collaborative robots require analysis of a wide range of issues, including the human experience perspective, to ensure safe and cost-effective operation. Below is a brief recollection of questions that could be asked when attempting to develop a comprehensive safety assessment strategy.

- How is the desired overarching production value specified and measured, and how are parameters such as installation time, product quality, work space requirements, change-over time, manual hoursand so on correlated to this desired value?
- How is sufficient safety defined and measured for situations where operators and robots work in direct contact?
- How is sufficient experience of safety defined and measured for human-robot collaboration?
- To what degree is sufficient safety achieved if existing standards and regulations, applicable for collaborative robots, are followed?
- How is the full range of methods for position detection of humans and human body parts, utilized?
- How is it ensured that the full range of methods for communication between operator and robot, including potential for thought control, is utilized in an effective way?
- How are possibilities to ensure operator acceptance utilized?
- How is role setting between operator and robot handled?
- How is assembly cell layout, including automation level, component logistic and point of transfer between autonomous robot operation mode and collaborative operation mode, handled?
- Is the strategy covering all different types of injuries, applications and types of robots?
- How is it ensured that a collaborative robot safety assessment strategy is integrated in existing company safety assessment strategies?
- How is it made sure that the strategy can be used for all business-decision phases: pre-studies, installations and operation?
- How are learning strategies such as reinforcement learning and deep learning utilized for rapid improvement of safety, productivity and automation level of collaborative robot installations?

Last but not least, ongoing technology development trends simultaneously increase the opportunities for collaborative robot solutions and reduce the need for these solutions as the front line of what can be 100% automated quickly moves forward. How is it ensured that the safety assessment strategy is continuously updated as technology advances?

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Robots are used in industry, rescue missions, military operations, and subwater missions. Their use in hazardous environments is crucial in terms of occupational safety of workers and the health of rescue and military operations. This book presents several hazardous environment operations and safe operations of robots interacting with people in the context of occupational health and safety.

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