

20240321_Evaluation_Of_Collaborative_Robots_V1.1

by Frazer Graham

Submission date: 21-Mar-2024 11:30AM (UTC+0000)

Submission ID: 227384930

File name:

17972_Frazer_Graham_20240321_Evaluation_Of_Collaborative_Robots_V1.1_461145_2079626325.docx
(6.77M)

Word count: 9307

Character count: 51348

An evaluation of a collaborative robot
capability for implementation into
explosive processing environments

by

Frazer Graham

Supervisor: Mr. David Holley

Project submitted as part of the requirements
for the award of BEng (Hons) OME

March 2023

Academic integrity declaration

I declare that:

- The report submitted has been written by me alone.
- The report submitted has not been previously submitted to this university or any other.
- That all content, including primary and/or secondary data, is true to the best of my knowledge.
- That all quotations and references have been duly acknowledged according to the requirements of academic research.

I understand that to knowingly submit work in violation of the above statement will be considered by examiners as academic misconduct.

21/03/2024

X

EKG

Frazer Graham

Mr

Signed by: Graham Frazer K

© Crown Copyright
Defence Science and Technology Laboratory UK

Approval for wider use or release must be sought from:
Intellectual Property Department
Defence Science and Technology Laboratory
Porton Down, Salisbury, Wiltshire SP4 0JQ

Abstract

To improve productivity, and safety, in explosive processing areas, research was conducted to produce a design proposal to automate explosive processing activities. To achieve this, discussions were hosted with stakeholders to determine functional and non-functional requirements for a device to handle energetic components.

During the product design process, collaborative robots were identified as a suitable solution due to their flexibility, re-configurability and safe working practices with human operators. However, before a cobot can be deployed into an energetic environment, data is required to ensure a cobot can safely handle energetic components. To achieve this a pick and place activity was undertaken with an UR3e cobot arm, and a component which contained force sensing resistors. The objective was to generate a force time curve to compare against small scale hazard data. Unfortunately, due to a pause on spending by Ministry of Defence Head Office the experiments were not completed.

Instead, a review was conducted to determine if the cobot was an appropriate procurement decision to satisfy the product specification requirements. Additionally, a review of the testing method was undertaken to determine relevancy to explosive small scale hazard testing methods.

Overall, it was determined a cobot, in theory, could improve safety as remote working could be achieved. However, to deploy the UR3e into an energetic facility the cobot arm requires further modifications, and procurement of equipment, to satisfy the authorising stakeholder requirements.

Keywords:

Energetic handling, energetic components, small scale hazard data, cobot assurance testing, remote processing, hazardous environments

Acknowledgements

In the south of England, on the coast, sits a small square office with frosted windows, a constantly ticking clock above the door, and an A3-whiteboard with a mountain of actions written down the side. In the centre of the room sits a Scotsman furiously typing, picking up phone calls, and pestering his colleagues about explosive safety, and configuration management.

That overburdened Scotsman was my first mentor. Luckily for me, during his speeches I could understand his accent. Otherwise, I could have lost a 'wee' bit of knowledge, which would have costed me this degree.

Thank you Allan for being a mentor, colleague, and friend.

Table of Contents

Academic integrity declaration.....	i
Abstract	ii
Acknowledgements	iii
List of Figures.....	vi
List of Tables.....	vii
List of Abbreviations	viii
1 Introduction.....	1
1.1 The Problem	1
1.2 Aim.....	2
1.3 Objectives	2
2 Background Research.....	4
2.1 Explosive Ordnance Disposal Robot.....	4
2.2 Propellant Mixing Robot.....	6
2.3 Commercial Robots	8
2.4 Collaborative robots and industrial robots.....	10
2.5 Background Research Summary	12
3 Product Design Specification.....	13
3.1 Non-Functional Requirements	13
3.1.1 Discussion Challenges.....	15
3.2 Functional Requirements	16
3.3 Pairwise Comparison, and Functional Metrics	20
3.3.1 Non-Functional Hierarchy.....	20
3.3.2 Functional Hierarchy	22
4 Product Procurement	24
4.1 Functional Means Analysis	24
4.2 Design Proposal and Feature Importance Chart.....	26
4.3 System Pugh	34
4.4 Procured System	36
5 Methodology.....	37
5.1 Safe System of Work	37
5.2 Functional Metrics.....	38
5.3 Pick and Place Test	40
5.3.1 Equipment	40
5.3.2 Variables	40
5.3.3 Method	41
6 Results	42
6.1 Funding Challenges	42
6.2 Data Collected	43
6.3 Future Steps and Predictions.....	44
7 Discussion	46

7.1 UR3e Evaluation	46
7.1 Evaluation of the pick and place test.....	47
7.2 Use Cases and next steps	48
8 Conclusion.....	50
9 Reflection	51
9.1 Project Management Reflection	51
9.2 Technical Reflection.....	54
9.2.1 Product Design:.....	54
9.2.2 QFD Experience:.....	55
10 References	56
11 Bibliography.....	58
Appendix A Requirements Importance Pairwise	60
Appendix B Quality Function Deployment.....	61

List of Figures

Figure 2-1 Haptically-Enabled Counter IED robotic system [5].....	5
Figure 2-2 KLM's Robotic Propellant Mixing System Proposal [7].....	7
Figure 2-3 Mapping of mine section and drilled holes (Top) [8].....	8
Figure 2-4 Robotic Quadruped working on an oil rig [9]	9
Figure 2-5 Industrial robots (left) and collaborative robots (right) [11] [12]	10
Figure 3-1 System Functional Analysis	17
Figure 3-2 Sub-routine Safety Flow Diagram	18
Figure 3-3 Sub-routine Operation Flow Diagram.....	19
Figure 3-4 Non-functional Pairwise Res	21
Figure 3-5 Functional Requirements Importance	23
Figure 4-1 Functional Means Analysis	25
Figure 4-2 System concept implementing COTS products.....	26
Figure 4-3 QFD-2	31
Figure 4-4 Feature Importance Chart	33
Figure 4-5 System Pugh.....	35
Figure 5-1 Functional Metrics Chart	39
Figure 5-2 Testing Positions.....	41
Figure 6-1 Gripper Force and Actuation Time Graph	43
Figure 6-2 Predicted Force Time Curve	44
Figure 9-1 Initial Project Proposal Timeline.....	52
Figure 9-2 Actual Project Timeline	53

List of Tables

Table 3-1 - Stakeholder Non-functional Requirements.....	14
Table 6-1 Gripper Actuation Time Results	43
Table 11-1 Requirements Pairwise Importance Table.....	60
Table 11-2 QFD-1	61

List of Abbreviations

AI	Artificial Intelligence
ADF	Australian Defence Force
CAD	Computer Aided Design
Cobots	Collaborative Robots
COTS	Commercial Off The Shelf
DERA	Defence Evaluation and Research Agency
DOF	Degrees of freedom
DSA	Defence Safety Authority
Dstl	Defence Science and Technology Laboratory
EE	Energetic Enclosure
ESW	Explosive Support Worker
EW	Explosive Worker
HO	Head Office
IED	Improvised Explosive Device
IoT	Internet of Things
JSP	Joint Service Publication
ML	Machine Learning
MOD	Ministry of Defence
OME	Ordnance Munitions Explosives
QFD	Quality Function Deployment
RAS	Robotic and Autonomous Systems
ROS	Robot Operating System
SOP	Safe Operating Procedure
SSOW	Safe System of Work
SHEF	Safety, Health, Environmental and Fire
SME	Subject Matter Experts
SQEP	Suitability Qualified and Experienced Personnel
UR	Universal Robotics
WI	Work Instruction

1 Introduction

'Were you expecting an exploding pen? We don't really go for that anymore.' – Q (Skyfall)

1.1 The Problem

Defence Science and Technology Laboratory (Dstl) is a UK Ministry of Defence (MOD) agency that provides world class expertise, and delivers cutting-edge science and technology for the benefit of the nation and its allies. As part of Dstl's responsibility to lead on MOD's science and technology programmes it has the capabilities to deliver work involving highly hazardous (chemical, biological, radioactive, and energetic) materials. [1]

Due to the nature of the work with hazardous materials, over the past few decades (1990 – present) there has been safety incidents involving biological, chemical and energetic materials. For example in [2] [3] the following incidents have been published:

- **Biological:** On the 6th of May 1999, Defence Evaluation and Research Agency (DERA), before being renamed to Dstl, received a crown censure due to a worker being potentially exposed to a hazard group three pathogen. [3]
- **Energetic:** On the 18th of February 2011, Dstl received a crown censure due to an energetic incidence involving the handling and preparation of charges for testing. Resulting in a death of a scientist. [3]
- **Chemical:** In February and March 2018, employees displayed symptoms of irritation following a process involving irritant products. The levels the workers were exposed to led to no harm or ill health, although control measures were reviewed and improved. [2]

As a result of these incidents Dstl continuously searches for improved working methods. A recent interest for Dstl is the use of collaborative robots (cobots) in energetic environments to improve safety, efficiency, and productivity.

By implementing cobot systems to process hazardous activities, Dstl can reduce personnel being exposed to hazardous environments, and (semi)-automate hazardous activities. Therefore, reducing risk to personnel through the use of greater hierarchy control measures.

1.2 Aim

The aim is to evaluate collaborative robot's capabilities for implementation into explosive processing environment. To determine if cobots are suitable to (semi)-automate energetic processes and achieve remote working to improve safety, and productivity.

1.3 Objectives

To achieve the aim, a quality function deployment (QFD) process will be implemented for the following mission statement:

“Using a cobot, safely pick and place energetic components.”

The purpose of this mission statement is to guide the QFD process for a generic pick and place cobot into an energetic processing facility. This will then unlock future research into different tools, and different applications of cobot' technologies within an energetic facility once competency and experience has been developed.

The benefits on implementing a QFD approach is that the final product is customer-centric. Additionally, the process will reduce development time and costs as it reduces design changes at later stages. Provided the requirements were identified correctly.

The disadvantages to QFD approach is the results are subjective to the team collecting the requirements. The team biases and perception of the problem will add weight to different requirements, and can therefore skew the design. Additionally, the process is resource intensive and can be very time consuming. As such only the following stages will be conducted:

- Literature review of robotic and autonomous systems working in energetic environments.
- The evaluation and capture of functional, and non-functional requirements from stakeholders to determine the product specification.
- The generation of a desired solution using Function Means Analysis, followed by a system Pugh to compare Commercial Off The Shelf (COTS) products.
- The identification of critical design features, and the development of testing regimes. The tests will then ensure any product procured can be evaluated to ensure the product satisfies the critical requirements.

Overall, utilising QFD, a product specification will be generated and the most critical features identified based on customer requirements and literature studies. Using the product specification, and critical features, tests will be conducted on the chosen COTS platform to ensure it can work safely in an energetic processing room to achieve the mission statement.

2 Background Research

“If we knew what it was we were doing, it would not be called research, would it?” – Albert Einstein

Due to the developments in Artificial Intelligence, Internet of Things (IoT), and robotic technologies, there has been an increase of Robotic and Autonomous Systems (RAS) developed within the explosive industry and other hazardous environments (Nuclear, and Chemical). [4]

2.1 Explosive Ordnance Disposal (EOD) Robot

For example, in 2015, S.Nahavadi, et al. [5] proposed a solution of a multi-point haptic teleoperation system to counter Improvised Explosive Devices (IED). In their design, they suggest a traversable platform with robotic arm and end-effector (tool). Additionally, they suggested the use of a stereo Pan Tilt Zoom (PTZ) camera system which enables the EOD operators to view the environment in 3D. The Australian Defence Force evaluated their design in which they successfully extracted 4 simulated detonators from PE4 explosives, uncovered mines without detonation, and cut strands of wire. Overall, the report identified the advantage for EOD operators by achieving a remote system.



Figure 2-1 Haptically-Enabled Counter IED robotic system [5]

As a result of their success it had identified the following requirements which should be adopted in Dstl's product specification:

- Pan, Tilt, Zoom Stereo Vision to improve vision, accuracy, and to enable 3D environments.
- A payload of 5Kg at full extension is considered sufficient for majority of EOD tasks.
- Velocity of $\pm 2 \text{ mms}^{-1}$ and acceleration of $\pm 5 \text{ mms}^{-2}$ for the end effector provides suitable prediction and control.
- Haptic feedback capable of producing bi-directional forces.
- Gripper's capable of moving, yawing, have high torque, emit minimal noise, and is capable of monitoring: local temperature, gripping force, and torque for internal/external grasping.

Another EOD application was the use of gesture control. Siddharth Narayanan and C.Ramesh Reddy [6] proposed a solution using machine learning to identify operator's gestures in order to control the end-effector. The objective was to remove user fatigue and to create a common controller. They successfully demonstrated a concept design. Unfortunately, they were unable to incorporate haptic feedback, and could not be adopted into Dstl's product specification due to the perceived value of haptic feedback.

2.2 Propellant Mixing Robot

An older report, 1988, by the Air Force Astronautics Laboratory shares the development of robotics applications in a solid propellant mixing laboratory [7]. While the source is dated, it can still be used to identify potential product requirements. Their study considers the:

- Protection of the robotic system from the hazardous environment.
- Consider the degrees-of-freedom of the robotic arm.
- Interfaces and control methods.
- Tooling requirements, and special features or fixtures to work in the environment.
- Connection of utilities such as power, compressed air and water.
- Spare parts, and maintenance routines.
- Facility requirements and laboratory layouts.
- Safety precautions for works in the local vicinity.
- Time to install safely into work environment while minimising cost to local area.
- Final cost of the device(s)

Overall the report is a successful feasibility study in which they identified a use case, and produced a concept design to achieve remote propellant mixing (Figure 2-2). Unfortunately, due to cost they were not able to begin phase 2 and integrate a solution. However, their identification has greatly assisted the development of Dstl's own product specification. It should be noted, consideration should be made of the information that is lifted from the document as technology or working methods may have changed since 1988.

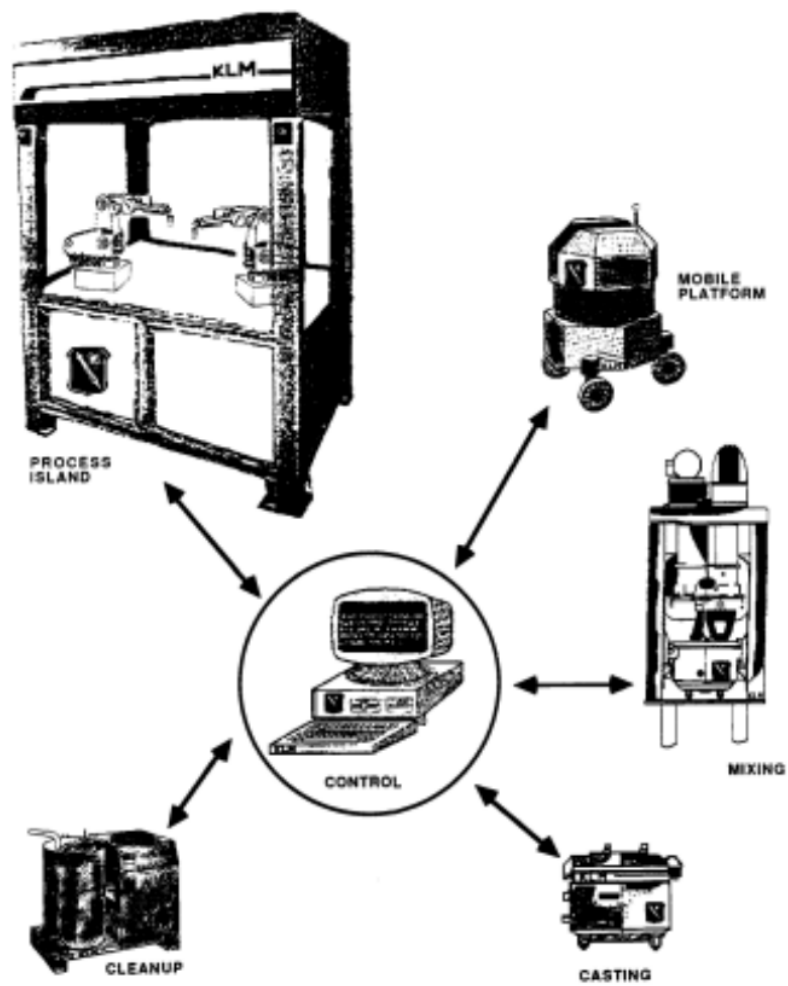


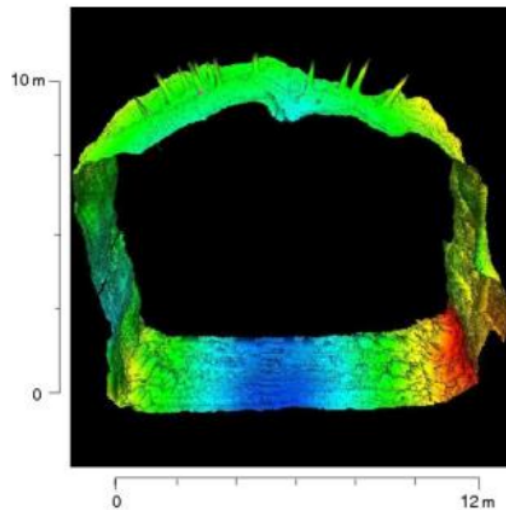
Figure 2-2 KLM's Robotic Propellant Mixing System Proposal [7]

2.3 Commercial Robots

In the commercial industry there have been developments of explosive robots for the use of preparing mining charges. The research by Adrian Bonchis et al. [8] proposed a hydraulic robotic system capable of identifying drilled holes, and insert primer-detonator assemblies. Within their requirements they identified:

- Mechanical manipulator with six degrees of freedom and encoders to track movement.
- Number of laser range-finders and LED lights to support identification.
- Surveying grade laser range finder which fits onto the tip of the end-effector.
- To move joints simultaneously adequate hydraulic flow rate, and pressure needs to be maintained.
- Integrating 3D mapping with lasers to identify tasks.

While Adrian Bonchis research was aimed commercially their work of integrating real time mapping (Figure 2-3) is highly valuable in an environment that may change. Additionally, the use of modelling and mapping will provide greater system self-awareness and enable greater data extraction from the models it can



produce.

Figure 2-3 Mapping of mine section and drilled holes (Top) [8]



Figure 2-4 Robotic Quadruped working on an oil rig [9]

Finally in 2014, Samuel Stavionha et Al [10] investigated the requirements and challenges within the Oil and Gas industry. Through their research they identified activities that robots could achieve, replacing the need and risk to operators.

Additionally, they investigated software, and physical requirements. In reference to Dstl, the system being developed does not need to survive harsh weather as it will be deployed into a lab environment. However, the report does focus on how to reduce the risk of fire, and consider explosive requirements in terms of ATEX and ruggedisation.

Important notes were:

- Robot must be certified for operation in explosive environments.
- Electronics must be suitable for explosive environments.
- The device shall operate in limit space and work on specialised flooring (conductive, anti-static).
- Could be controlled manually, semi-automatically or autonomously.
- The device must operate between -30 and +50 degrees Celsius, and operate in humidity up to 100%.
- Must display warnings messages, and signals during errors or abnormal situations are detected.

- Achieve tasks such as monitoring, inspection, and be easily programmable for new routine activities.
- Tooling must be easily exchangeable and ATEX certified.

Overall, Samuel Stavionha et Al [10] has identified requirements for RAS technologies to support off-shore oil rig activities. However, their focus on software, and programming has given better insight into robust ability when an error occurs.

2.4 Collaborative robots and industrial robots

To understand collaborative robots, an understanding of industrial robots is required. In the work Collaborative Robots and Industrial Revolution 4.0, F. Sherwani, Muhammand Mujaba, and B.S.K.K Ibrahim identified an industrial robot as large, heavy, rigid bodies for difficulty and dangerous human activities (Figure 2-5). To protect workers they are usually isolated on the workshop floor, and are usually task specific.



Figure 2-5 Industrial robots (left) and collaborative robots (right) [11] [12]

Collaborative robots (cobots) are designed to work alongside humans, sometimes operating in the same vicinity as the operator. [4] Identifies the advantages of implementing cobots as:

- **Fast Redeployment.** As cobots can be programmed through manual movement, the skill required to redeploy a cobot is less than an industrial robot. As a result smaller tasks not usually considered can be automated

through the deployment of a cobot. Industrial robots require computer programming which requires specialist knowledge and skills.

- **Improved Safety.** Due to the operating speeds, and force sensors integrated into the system, some cobots have the ability to stop operation upon the detection of a resistance force. Additionally, some cobots have methods to vary their speed based on an operator's vicinity to the work bench. Demonstrating cobots have the ability to balance productivity and safety based on human's location. Unlike industrial robots in which human operators cannot co-exist with machine and result in down-time in the event of human interaction.

Overall the report summarises that a collaborative robot has a greater return of investment than traditional industrial robots due to the above advantages. Due to a lower skill, investments costs, and adaptability of the system it can be quickly deployed to automate smaller tasks while remaining flexible.

2.5 Background Research Summary

In summary, robots are being used in explosive environments, both commercially and for defence. All reports [5, 7, 8, 10] agree that robots in explosive environments reduce the risk to personnel due to remote working. Additionally, they also mention other benefits such as productivity, and efficiency. The proposed designs in [8] demonstrate how robotics, and modelling could be utilised together to create 3D environments. These models and environments would then increase robotic accuracy and self-awareness to execute tasks.

Furthermore, the reports [5, 7, 10] provide a high level of detail regarding requirements and considerations in terms of software, integration, hardware, and design considerations in regards to industry standards (ATEX, and Explosive Regulations). A foundation of requirements from [5, 7, 10] can be extracted to achieve Dstl's aims in regards to robotics devices.

Finally, it has been indicated that a collaborative robot device will be better suited to achieve the mission statement, than a traditional industrial robot. The advantage of utilising a cobot is faster repayment time, and no requirement to understand programming. While a cobot may be restricted in terms of payload, and operating speed, its slower speed and force sensors would improve safety of working with energetic materials. [4] [11] Overall, a collaborative robot device shall be implemented to achieve the mission statement.

3 Product Design Specification

“The only important thing about designs is how it relates to people.” – Victor Papanek

To determine Dstl's requirements an internal review was conducted with the aid of background knowledge. The aim was to establish both functional and non-functional requirements to generate a design specification.

3.1 Non-Functional Requirements

To identify the non-functional requirements an internal review was conducted which consisted of Subject Matter Experts (SME) from team members who worked in:

- Explosive Safety
- Safety Health Environment and Fire (SHEF), known commonly as health and safety.
- Facility Management for the Energetic Enclosure (EE)
- Explosive Support Workers (ESW)
- Robotic and Autonomous Systems (RAS)

Feedback was collated into Table 3-1 for a robotic device to handle energetic components. These requirements, alongside those determined from background research have been combined into Table 3-1.

Stakeholder	Requirement	Specification
Operator	It must have electrical optical vision.	Stereo Pan Tilt Zoom Cameras and multiple joint cameras.
Operator	It must be able to detect movement.	Detect humans working in vicinity (5m radius)
Operator	It must be able to handle 5Kg at full extension	5 Kg
Operator	It must be able to approach the workpiece from different directions.	6 Degrees of freedom
Operator, SHEF, ESR, FM	It must be able to report working temperature.	Surface temperature no greater than 85 degrees Celsius. Ideally operate between (-30 and +50 degrees Celsius)
Operator	It should integrate ML and AI	True / False
Operator	It should integrate CAD, CT models	True / False
Operator	It should be programmable in different languages	C++, Matlab, G-code, python
Operator, FM, ESR	It should be easily maintained	True / False
Operator, SHEF	It should have a range of movement and acceleration speeds.	Velocity of 2 mm/s and acceleration of 5 mm/s ² . No greater working velocity than 0.5 m/s
Operator	It should be able to reach 1.5m	1.5m reach
Operator	It should be able to be transported	Lifted by people, fork lift, or lifting aids
Operator	It should have infrared vision	True / False
SHEF, ESR, Operator	It must stop when instructed	Instantly (>5 seconds)
SHEF, ESR, Operator	It must not move during power loss	Plus or minus 1mm
Operator	It must be able to quickly change tools	Manually or Automatically (> 5mins)
ESR	It must adhere to explosive regulations and statutory law	CAT A, Zone 0, 1, 2, 1G (DSA 03 OME Part 2, ATEX)
SHEF	It must be able to work safely with humans	ISO / TS 15066:2016
Operator	It must be able to be remotely controlled	True / False
Operator	It must be able to be remotely programmable	True / False
Operator	It must have haptic feedback	Bi-directional forces
SHEF, ESR, Operator	grippers must not crush components	True / False
Operator, FM	It must be fixed to a variety of surfaces and angles	0 - 180 degrees
Operator	Errors must be identified to the user.	Pop up prompts
Operator	The device must be easily manipulated.	Manually adjusted or intuitively controlled via controller/program
ESR	Grippers must not apply friction, electrical, static or impact	True / False (DSA 03 OME Part 2, ATEX)

Table 3-1 - Stakeholder Non-functional Requirements

3.1.1 Discussion Challenges

During the discussions it should be noted there were concerns in terms of explosive licencing (approval) and technical capability. Team members were cautious to contribute and embrace the idea of a new process. Possible reasons are:

- **Fear of job displacement.** There is a common concern that robots are being developed to replace workers. To reassure team members, it was justified that the device will be a tool in which their experience is still required for efficient operation. However, this had little effect to persuade the team members.
- **Fear of technology readiness level.** Many team members were pessimistic about what current technology could achieve. Due to the environment and processes that are conducted, Explosive Workers (EW) did not believe a robot could adapt to new stimulus and change in procedure. As a result team members were not enthusiastic to share potential case studies in which it could be deployed.
- **Fear of Compliance.** Due to Dstl's processes, many workers, and team members could not see a device being implemented into an energetic environment. Therefore, discussions should be made with regulators and authorising parties to ensure easier transition and introduction of robotic technologies in explosive licenced facilities.

A possible cause for these concerns are due to the fact there is minimal exposure to robotics devices. As a result there is no method to challenge perception of current technologies capabilities. It is recommended to ask team members to attend trade shows, or provide a demonstration piece to assist stakeholder engagement. As such it should be noted that all non-functional requirements may not be present in Table 3-1 from stakeholders due to negative perception of emerging technology.

3.2 Functional Requirements

To identify all functional requirements, a functional analysis technique was employed. This was achieved without SME input due to the challenges mentioned in section 3.1. However, background research was referenced to aid the identification of functional requirements.

The functional analysis consists of three flow charts. The overall system flow chart (Figure 3-1), which allows a user to execute a pick and place routine from start to finish. A sub-routine called safety (Figure 3-2), and another sub-routine called Operation (Figure 3-3).

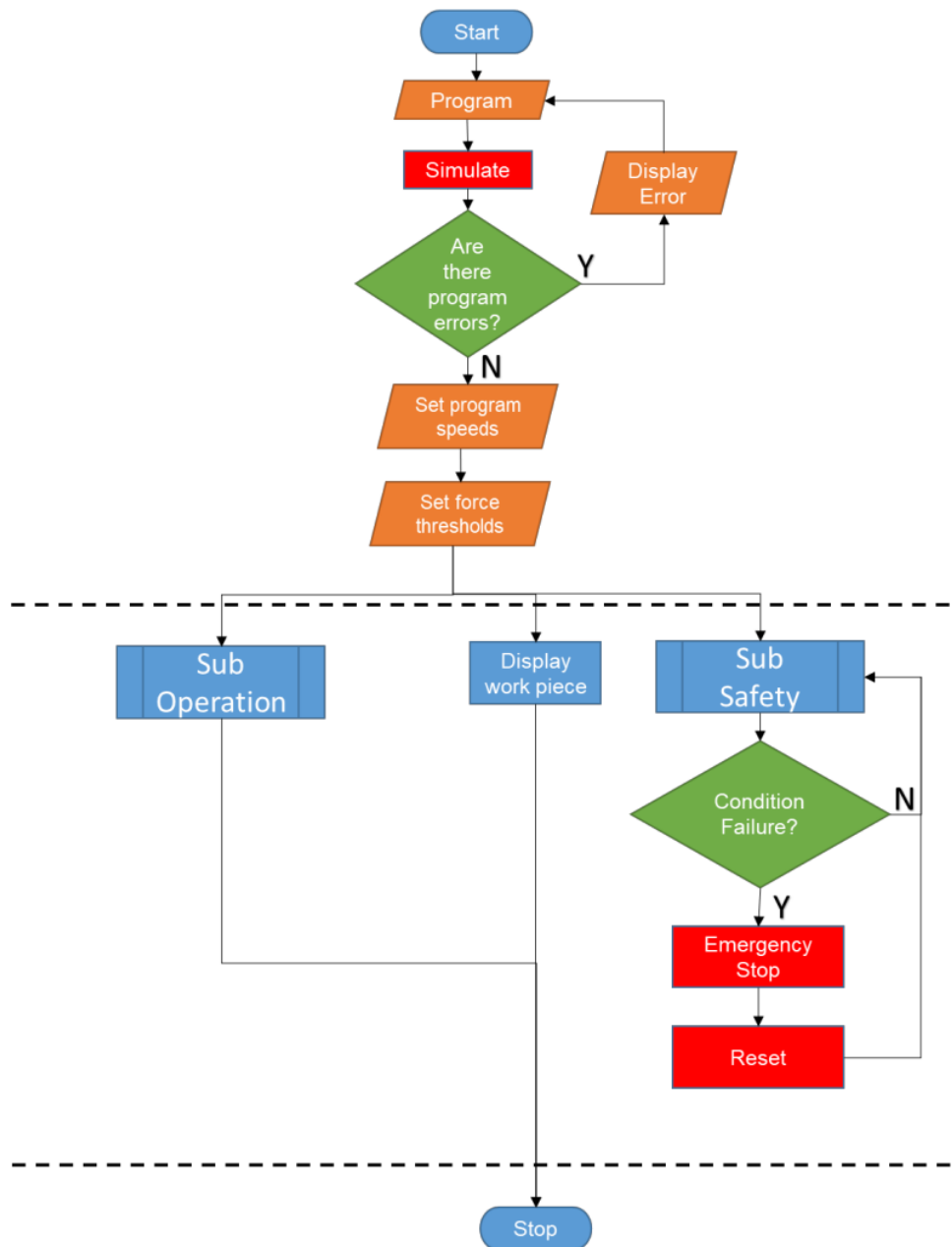


Figure 3-1 System Functional Analysis

- Sub routine Safety (Figure 3-2) is a process to monitor the systems force, speed, temperature, local environment, emergency stop (e-stop), and potential chemical reactions. This sub routine checks the values for each of these conditions and returns the value to the main program. If any of these conditions exceed a set threshold the emergency stop will function followed by a notification to the user of the error. This routine is continuously checked as Sub Operation is being executed.

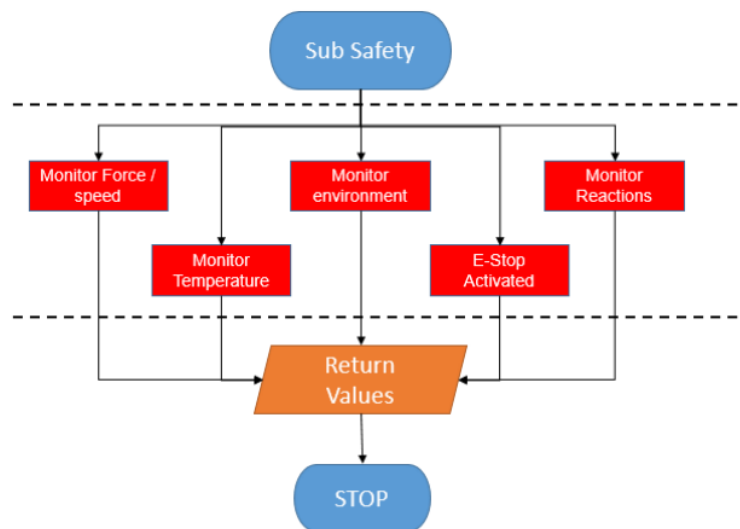


Figure 3-2 Sub-routine Safety Flow Diagram

- Sub Operation (Figure 3-3) is the end-to-end process of a tool being selected, equipped, and utilised to pick and place an energetic component. Throughout the routine there are three checks. One to verify the tool has been correctly selected, one to ensure the component has been correctly gripped, and finally a check to ensure the component has been moved to the desired position.

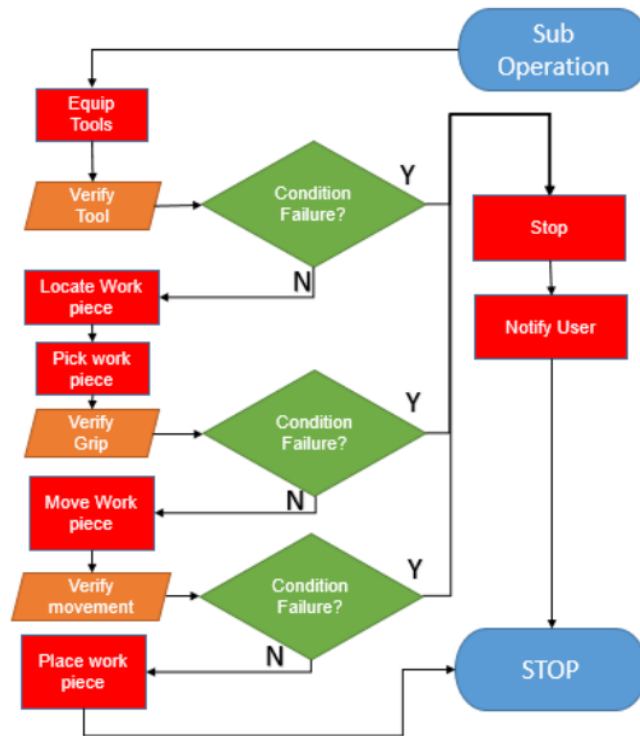


Figure 3-3 Sub-routine Operation Flow Diagram

Overall Figure 3-1 is limited due to little stakeholder engagement. However, as a minimum, it does satisfy the mission statement. Once stakeholder engagement has been achieved these flow charts should be reviewed to introduce new functions. It is proposed the overarching flow chart remains similar as a foundation. New tasks can be easily bolted on as new sub-routines in which the program will decide which one to call. The benefit of this is to reduce time in the future to develop specific applications.

3.3 Pairwise Comparison, and Functional Metrics

To adequately develop or procure a system which achieves the stakeholder non-functional and functional requirements a pairwise comparison, and functional metrics graph was produced. These were achieved by comparing non-functional requirements against one another to create a hierarchy. The non-functional requirements with their importance were then compared to the functions identified from Section 2.1 and assigned a value based on their relation. This allowed the value of the functional requirements to be identified.

3.3.1 Non-Functional Hierarchy

Figure 3-4 displays the hierarchy of non-functional requirements. The most important requirements are that it must adhere to explosive regulations, work safely with human, not crush components, and grippers must not apply friction, electrical or static impact. The least important are the integration of AI, Machine Learning (ML), Computer Aided Design (CAD), and programming language. Based on the concerns from Section 3.1.1 the hierarchy seems adequate as it incorporates the stakeholder concerns.

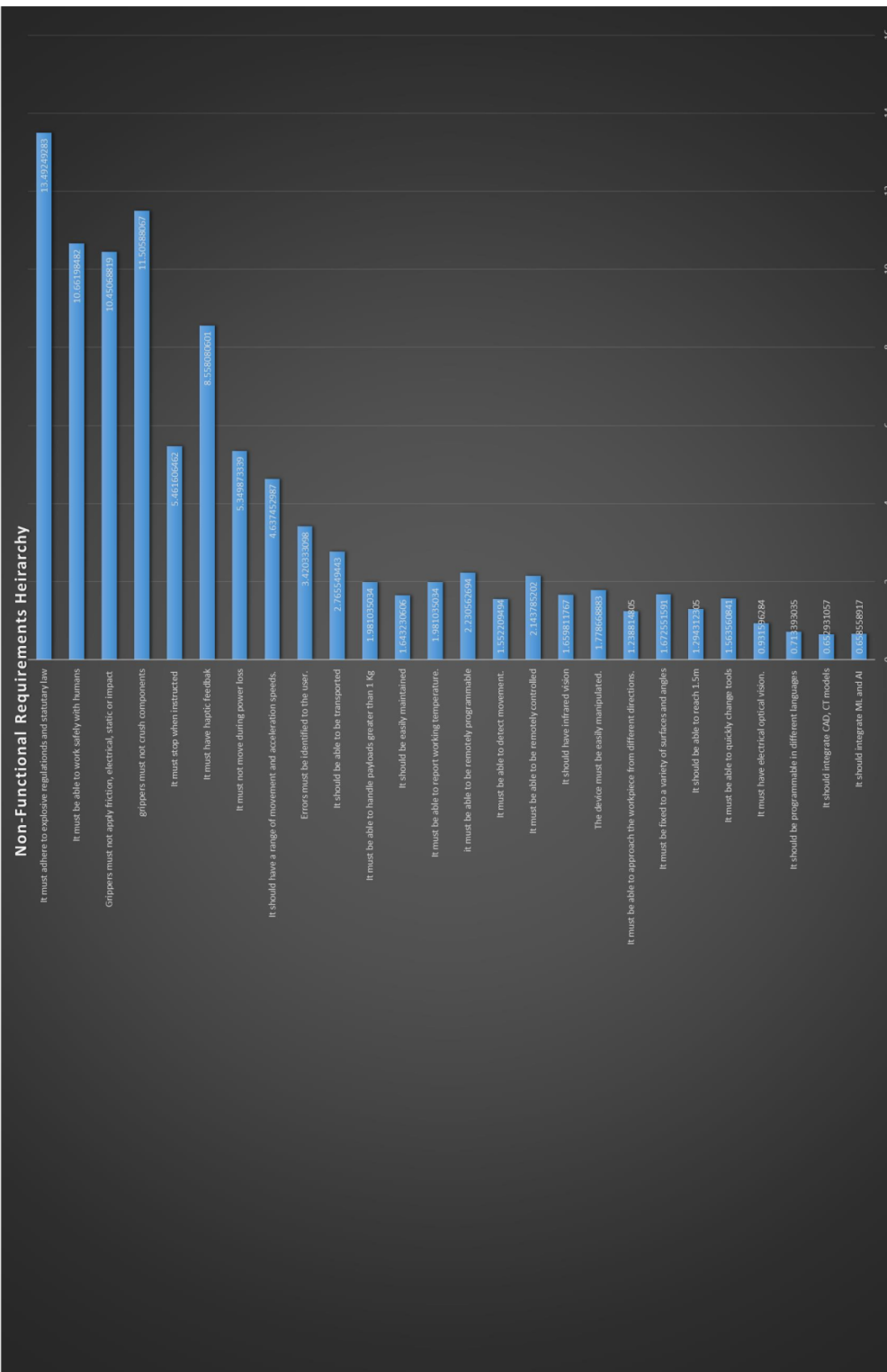


Figure 3-4 Non-functional Pairwise Res

3.3.2 Functional Hierarchy

Figure 3-5 displays the hierarchy of functional requirements. The most important functions are that the system can detect forces, its ability to emergency stop, and the speed the system operates.

Detecting forces is crucial for the system to avoid crushing components during operation. Additionally, it can assist in operation to detect anomalies in terms of unusual resistance force being detected. Thus allowing the identification of non-routine tasks.

The emergency stop is a critical feature to prevent accidental ignition of energetic components. However, the E-stop is based on the sensors which monitor the environment and the movement of the platform, and therefore could be argued to be a lower requirement. Ultimately, the E-stop is an important feature as it will reduce the effect of undesired stimuli which could lead to accidental ignition.

Furthermore, control speeds are important. As mentioned in the background research, the correct control speeds can make the system better to control [5]. Additionally, the speed is important for safety if it is to work with alongside humans. If the system can be controlled to work at different rates then it will allow a better management of safety, efficiency, predictability, and improves worker-robot relation.

Finally display work-piece has been rated the least important function. This is due to the current facilities have remote vision. However, this should be reconsidered. As the background research suggest the incorporation of Tilt, Zoom, Pan Stereo Vision systems improve the co-ordination of remote tooling.

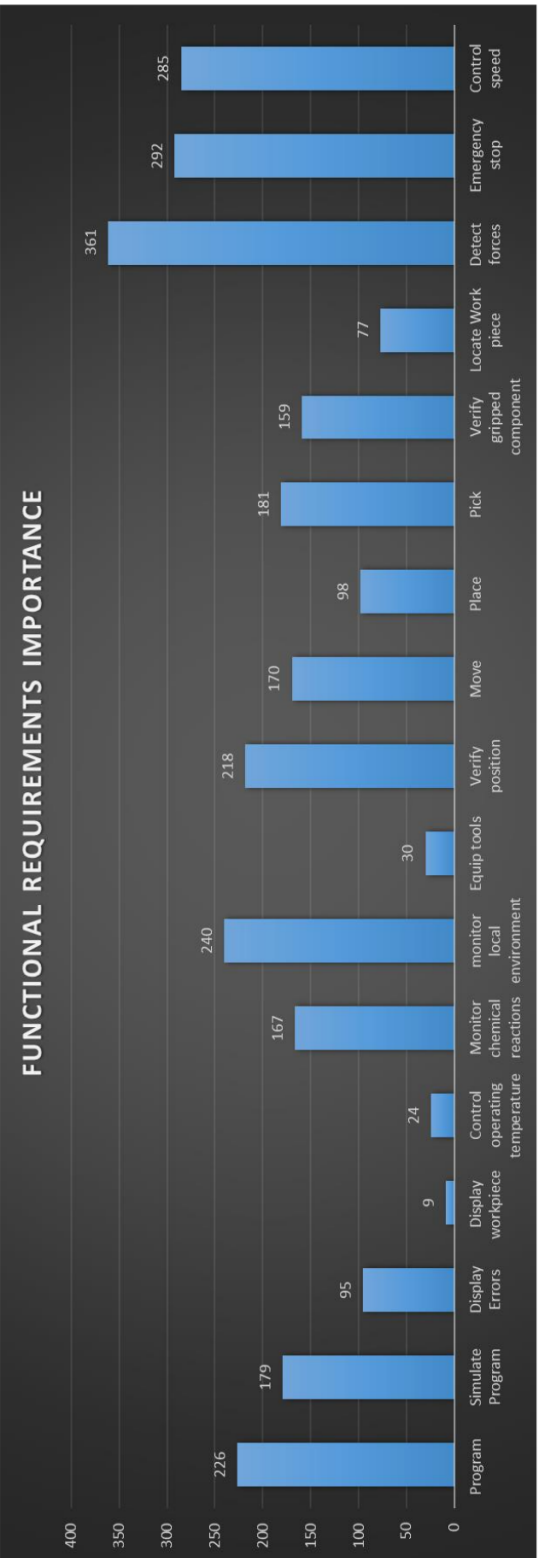


Figure 3-5 Functional Requirements Importance

4 Product Procurement

“You have to want it enough to buy it.” – Lailah Gift Akita

To identify a suitable system to achieve the mission statement a functional means analysis, QFD 2, and system Pugh was conducted. This set of steps enables a bespoke design to be proposed based on the requirements; while also introducing Commercial Off the Shelf (COTS) products which can then be compared against the bespoke design. This comparison of existing products against stakeholder requirements, and proposed design could lead to identification of a suitable COTS product saving time and resources.

4.1 Functional Means Analysis (FMA)

Based on the design specification a functional means analysis (FAM) has been conducted. This process aims to identify different methods to achieve a function. For example: for the system to pick up an energetic component the following means could be utilised: Suction, Soft-Grippers, Magnetic Grippers, and Mechanical Grippers.

Figure 4-1 has been achieved by utilising background knowledge to identify technologies which are capable achieving each function. Additionally, market research has been conducted to determine COTS products which could be implemented. This method been achieved through online research and attendance of trade shows which demonstrated cobot technologies and tooling.

The benefit of a functional means analysis is that different solutions can be identified and quickly compared. However, the disadvantages is the method is restricted to the participant's knowledge of existing technologies.

Function	Means										Machine Code	High Level Language
Program	PC	Tablet	Phone	Memory Stick	Wirelessly	Wired	Drag and drop	Machine Code	High Level Language			
Simulate Program	PC	Tablet	Digitally	Virtual Reality	Unreal Engine	Unity	CAD					
Display Errors	Noise	Lights	Display Messages	Mechanically	Syntax errors							
Emergency stop	Mechanical E-Stop	Thermal Sensors	Lidar Sensor	Radio-waves	Lasers	Programmed E-stop	Force Torque Sensors	Chemical Reaction Detection				
Display workpiece	Camera	Infra-red	Radar	LIDAR	RF							
Control speed	Variable Dials	Programmed Buttons	Supply Voltage / Current	On - Off Switches	Variable Programmed							
Control operating temperature	Heat Sinks	Fans	Liquid Cooling	Paint / Colour	Surface Area							
Monitor chemical reactions	Infra-red	Machine Learning	Optical Vision	Hyper-spectral camera								
monitor local environment	Camera	Infra-red	Lasers	LIDAR	Radio-waves							
Equip tools	Automatic Tool Changer	Rotating Gantry	Manual Tool Change									
Pick	Friction Gripper	Jaw Gripper	Magnetic	Suction	Needle	Electrostatic	Van-der Waals	Acoustic	Bernoulli			
Move	Compliant System Design	Mechanical System Design	Electric Motors									
Place	Friction Gripper	Jaw Gripper	Magnetic	Suction	Needle	Electrostatic	Van-der Waals	Acoustic	Bernoulli			
Verify position	Compliant System Design	Open System	Semi-Open System	Closed System	Lasers	Lidar	Vision	Electrically				
Verify gripped component	Force Sensor	Electric	Light	RF	LIDAR	Laser	Magnetic					
Locate Work piece	Camera	Infra-red	RADAR	LIDAR	RF	Colour Detection	Shape Detection	Machine Learning				
Detect forces	Force Sensors	Closed Loop Circuit (movement)	Voltage / Current									

Figure 4-1 Functional Means Analysis

4.2 Design Proposal and Feature Importance Chart

From the FMA process the following solutions were chosen:

- ATEX Tablet, with drag-and-drop programming and the ability to display error and warning messages.
- LED's, and beacons to display visual warnings and error messages. Additionally, to provide light in dim scenarios.
- Vision system incorporating ruggedized Pan Tilt Zoom Cameras, and Infra-red vision.
- The device should be powered with electric motors, which are also encoded to accurately determine movement.
- The device should have force sensors within both the platform, and the end-effector to determine motor loading, and movement.
- The end-effector should be manually changes, and the system should not exceed working temperatures as it will be passively cooled.
- Finally, it will have E-stop buttons for users to activate or for the system to activate based on the programmed thresholds.



Figure 4-2 System concept implementing COTS products

Using the FMA, the second stage of the QFD process can be achieved (QFD 2). Using the functions and the chosen means to achieve those functions, a value can be assigned to how they interact with one another. QFD-2 shows how each mean correlates to the function (0 none, 3 Low, 6 Med, 9 High). From the values entered on Figure 4-3, Figure 4-4 can be generated providing a features importance chart.

Design feature	Importance	Tablet	Drag-and-drop	Display Messages	E-Stop Button	Force Sensors	Camera	Programmed Operating Settings	Passive Cooling	Intra-red Vision	Manual Tool Changer	Gripper	Electric motors	Encoder	End-effector force sensor	Motor Loading	Functionality Detail
Functionality																	Python, C++, Matlab, G-Code, ROS
Program	23	9	9	9				9									Sections of program, or end-to-end process
Simulate Program	18	9	9	9				9									Programming errors, movement errors, equipment connection errors
Display Errors	10	9	9	9		9				9	9	3	6	6	9		Stereo Pan/Tilt Zoom Cameras and multiple joint cameras
Display workspace	1	9					9			9							Surface temperature no greater than 85 degrees Celsius. Ideally operate
Control operating temperature	2	9					9		9	9		6	9		3		Thermal, gas, colour, steam, bubbles, odour
Monitor chemical reactions	17						9			9	6	6	3				Detect personnel, movement of workpiece, 5m radius
monitor local environment	24						9			9	9	9					Automatically, manual
Equip tools	3			3	3	9					9	9					Plus or minus 2 mm
Verify position	22	9		9	9	9	9	3				9	9	9	9	9	Items >5Kg, various shapes and sizes
Move	17				9	9		9				9	9	9	9	9	Items >5Kg, various shapes and sizes
Place	10						3	9				9					Items >5Kg, various shapes and sizes
Pick	18				6		3	9				9					Items >5Kg, various shapes and sizes
Verify gripped component	16	9		9	9		9	9		9		9		9	9		Plus or minus 2 mm
Locate Work piece	8				3		9	9				9			9		Plus or minus 2 mm
Detect forces	36	9			9							9	9			9	Plus or minus 1N
Emergency stop	29			9	9			9	9	9	9	9	9	9	9	9	Instantly (>5 sec)
Control speed	29	9	9	9	9			9				9	9	9	9	9	Instantly (>5 sec)
		1401	707	1061	1477	462	866	1674	284	802	520	2031	1344	1069	1800	1193	velocity or 2 mm/sec; or acceleration in g mm/s ² . No greater working velocity than 0.5 m/s
Target																	
Benchmark																	
Ideal Value																	
How Much???																	

Figure 4-3 QFD-2

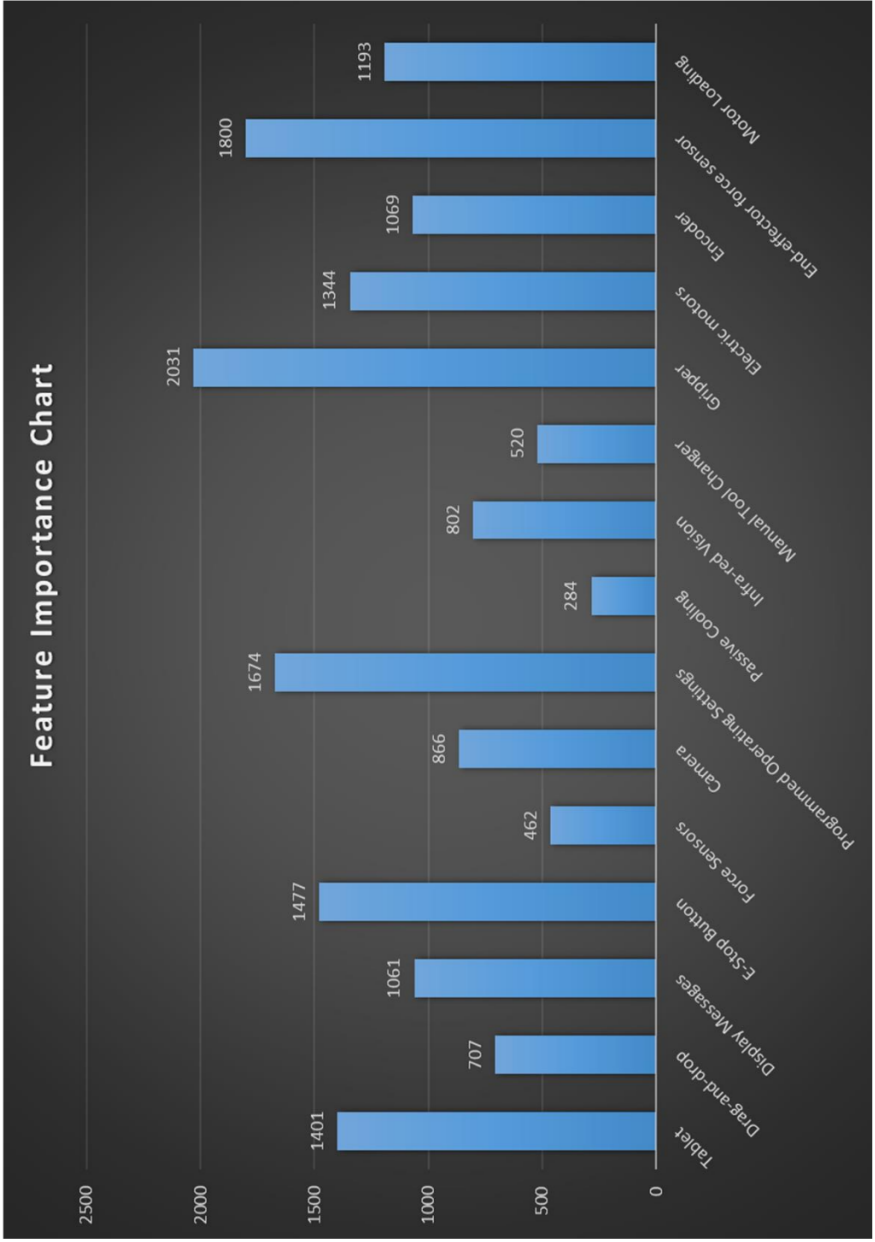


Figure 4-4 Feature Importance Chart

Figure 4-4 visibly identifies critical components in the required system. For example: it has been identified the gripper, and end-effector force sensor are the most crucial in the design. This is most likely due to the risk of potential fire and explosion if the component incorrectly grips or crushes the component. The benefit of this graph is that it highlights where the most resources should be allocated in the final design. It would be more beneficial to invest into a system which could grip a component, compared to a system which could efficiently passively cool itself.

Overall, a design has been proposed utilising a cobot device to achieve the pick and place of energetic components. The functions and means have been identified as well as the specification to achieve those functions and means.

4.3 System Pugh

Based on the proposed design in section 4.2 a system Pugh has been conducted comparing the proposed design against existing technologies. The aim is to reduce development cost and time by integrating and procuring existing technologies and combining systems where appropriate. The proposed design has been given a baseline of 1 across the board. If the market product has achieved above and beyond the required specification a score of 2 has been recorded. If the market product achieves below the required specification a zero has been recorded. Figure 4-5 displays cobot arms capable of pick and place routines, against the design concepts.

Four companies were approached for market research. These were Universal Robots (UR), Fanuc, ABB, and Kuka. An additional requirement which was not recorded during the proposal was: Security. Due to nature of the work some solutions were not feasible due to the data on the systems would be saved to an unsecured network, and therefore could not be utilised.

			Relative Importance Equal	Relative Importance Weighted	Concept Proposal	Universal Robotics	ABB	Kuka	Fanuc	Comments
WHATs - Customer Requirements		How much:- From QFD 1								
It must have electrical optical vision.		Stereo Pan/Tilt Zoom Cameras and multiple joint cameras.	1	1	1	0	0	0	0	No models inherently have vision, however, products can be brought.
It must be able to detect movement.		Detect humans working in vicinity (5m radius)	2	1	1	0	0	0	0	Safety guards can be procured at additional cost.
It must be able to handle payloads greater than 1 Kg		5 kg	2	1	1	0	0	1	0	Kuka has best cobot arm to handle components.
It must be able to approach the workpiece from different directions.		6 Degrees of freedom	1	1	1	1	1	1	1	All have minimum 5 DOF
It must be able to report working temperature.		Surface temperature no greater than 50 degrees Celsius. Ambient temperature between 1-50 degrees Celsius.	2	1	1	1	1	1	1	
It should integrate ML and AI		True / False	1	1	1	2	1	2	1	UR and Kuka can integrate with CAD / CAM packages
It should integrate CAD, CT models		True / False	1	1	1	2	1	2	1	UR and Kuka can integrate with CAD / CAM packages
It should be programmable in different languages		C++, Matlab, G-code, python	1	1	1	1	1	1	1	Each have own bespoke programming language and ROS
It should be easily maintained		True / False	2	1	1	0	0	0	0	Maintenance contract required
It should be programmable and acceleration speeds.		Velocity of 2 m/s and acceleration of 5 mm/s ² . No greater working velocity than 0.5 m/s.	5	1	1	1	1	1	1	
It should be able to reach 1.5m		1.5m reach	1	1	1	0	0	0	0	Smallest models do not have reach of 1.5m. Larger units available.
It should be able to be transported		Lifted by people, fork lift, or lifting aids	2	1	1	1	1	0	1	Kuka is the heaviest device.
It should have infrared vision		True / False	2	1	1	0	0	0	0	No models inherently have IR, however, products can be brought.
It must stop when instructed		Instantly (<4 seconds)	7	1	1	1	1	1	1	All models have emergency stop and work in accordance to ISO 13066
It must not move during power loss		Plus or minus 1mm	6	1	1	1	1	1	1	
It must be able to quickly change tools		Manually or Automatically (> 5mins)	1	1	1	0	0	0	0	Manual tool changing, however can be upgraded.
It must adhere to explosive regulations and statutory law		CAT A, Zone 0, 1, 2, 10 (ISA 03 ONE Part 2, ATEX)	17	1	1	0	0	0	0	Would need to request ATEX variant.
It must be able to work safely with humans		ISO / TS 15066:2016	13	1	1	1	1	1	1	
It must be able to be remotely controlled		True / False	2	1	1	1	1	1	1	
It must be able to be remotely programmable		True / False	2	1	1	1	1	1	1	
It must have haptic feedback		Bi-directional forces	6	1	1	0	0	0	0	Haptic feedback would require additional tooling / upgrades
Grippers must not crush components		True / False	9	1	1	0	0	0	0	Unknown, experiments required.
It must be fixed to a variety of surfaces and angles		0 - 180 degrees	1	1	1	1	1	1	1	
Errors must be identified to the user.		Pop up prompts	3	1	1	1	1	0	1	Kukua is programmed with low-level language, and may be more difficult to bugplat
The device must be easily manipulated.		Manually adjusted	1	1	1	1	1	1	1	Waypoints can be manually programmed.
Grippers must not apply friction, electrical, static or impact		True / False	10	1	1	0	0	0	0	Grippers are procured separately.
Delivery Time		As fast as possible	0	9	1	2	1	1	2	UR, and Fanuc has fastest lead times which will achieve 2022 / 23 FY procurement deadline.
Network Security		No data transfer	0	9	1	1	1	0	1	
Cost		As low as possible	0	9	1	3	2	0	0	UR cheapest, Kuka most expensive.
			100	53	48.5000566	47.25421108	45.44028211	47.25421108		
					71	51	25	42		
					153	120	98	70	89	
Ranking										

Figure 4-5 System Pugh

4.4 Procured System

From the results achieved in the System Pugh, Dstl decided to procure an UR3e cobot arm. This was due to UR being deemed the market leader. Additionally, the UR3e model supported unwritten financial requirements for the financial year 2022 / 23. The major disadvantages of this system is that compared to other models it has a smaller payload, and is not ATEX rated. However, the procurement of this system enables the following opportunities:

- Development of suitable experienced and qualified personnel (SQEP) who will be able to operate and deploy cobot technologies within the workplace.
- The development of concept demonstrators to tackle negative perceptions of cobot technologies, with chance to enhance stakeholder engagement.
- Testing of the Universal Robot family platforms and tooling. The tools are designed to be accessible to all UR cobots. Therefore, testing of the end-effector can be achieved on a smaller model without the procurement of a larger platform. Therefore, concepts tests can be achieved.

Overall despite the platform unlikely to be deployed into a hazardous environment to achieve its function, the lower cost, and implementation time will allow Dstl to conduct assurance testing to determine if Cobots are suitable for the application into hazardous environments.

5 Methodology

"The true method of knowledge is experiment." – William Blake

5.1 Safe System of Work

Dstl procured an UR3e collaborative robot to be used for research and development purposes rather than for deployment into processing facilities. However, before tests could begin, a safe system of work was implemented to work alongside the robot.

To establish a SSOW the following sub-activities were conducted:

1. Facility Inspection. The cobot arm remains within an engineering facility. An inspection was conducted prior to installation to inspect emergency exits, fire extinguishers, pat tests conducted and in-date, first aiders identified and labelled, access and egress, and general building cleanliness. The objective was to ensure good housekeeping and identify hazards.
2. Hazard Identification (**DSTL/DOC150588**). Using the documentation provided by Universal Robotics (UR) which identified hazards working with the cobot, and Dstl's own hazard checklist, a hazard identification process was conducted. Additionally, notes recorded from the facility inspection was used to aid the identification of hazards.
3. Risk Assessment (**DSTL/DOC150576**). A draft risk assessment which captured the risks identified from the inspection, hazard identification, and UR documentation was proposed. The initial ratings of the risk were considered low due to the operating speeds of the cobot and its payload (3Kg). During the review, it was agreed the building risk assessment

covered all risks identified, and it was not needed provided a safe operating procedure listed safe working practice.

4. Safe Operating Procedure (SOP) (**DSTL/DOC151168**). The SOP contains details relating to what personal protective equipment (PPE), training, and authorisation is required to safely operate the cobot arm. Within the documentation work was conducted with the Building Facility Manager to authorise who could access the room, and use the equipment. It also describes how certificates would be handled and authorisation updated.

It is proposed that these steps shall be repeated before implementing into an explosive environment. Unlike the workshop, care should be made to explosive category, explosive permits to work, and authorisation from the EE Facility Manager to install the cobot arm. Additionally, inspections should be conducted to ensure fire extinguishers are present in date, and emergency fire exits are available.

5.2 Functional Metrics

To build SQEP, and confidence within the system, assurance testing is required. The objective of assurance testing is to determine if the system can achieve the operating parameters established within QFD 1 and QFD 2. Based on the critical features identified in QFD 2, the top two features will be tested. This is to ensure if the product can achieve the required threshold.

Figure 5-1 displays a functional metrics chart with the two highest rated features (Gripper and Emergency Stop respectively). The requirements are labelled on the left, and the two functions along with their relation are in the first two columns. To the right of the column 'Emergency Stop' are the different tests that could be executed to inspect the critical functions. 3's represent a small correlation

between the test, and the requirement. 9's represent a high correlation between the test, and the requirement.

From Figure 5-1 it can be determined an effective test is the Gripper Pick and Place. By conducting this experiment, a wide range of requirements can be tested.

Function:- (Insert Specific function here) Test method and relationship to requirements		Importance		Detect Forces (Arm and End-effector)		Emergency Stop	Palletizing Rate Test	Emergency Stop Test	Breaker (Fuze) Test	Safety Proximity Sensors	Gripper Pick and Place
Requirements											
It must have electrical optical vision.		1									
It must be able to detect movement.		2				9				9	3
It must be able to handle payloads greater than 1 Kg		2									
It must be able to approach the workpiece from different directions.		1									
It must be able to report working temperature.		1									
It should integrate ML and AI		2									
It should integrate CAD, CT models		1									
It should be programmable in different languages		1									
It should be easily maintained		2									
It should have a range of movement and acceleration speeds.		5	9	9	9	9	9				
It should be able to reach 1.5m		1									3
It should be able to be transported		2									
It should have infrared vision		2									
It must stop when instructed		7	9	9	9	9	3	9	3	9	3
It must not move during power loss		6				9					
It must be able to quickly change tools		1									
It must adhere to explosive regulations and statutory law		17									
It must be able to work safely with humans		13	9	9	9	9		9			
It must be able to be remotely controlled		2									
It must be able to be remotely programmable		2									
It must have haptic feedback		6	9								3
grippers must not crush components		9	9				3				9
It must be fixed to a variety of surfaces and angles		1									
			361	292	92	195	75	210	160		
			Plus or minus 1N	Instantly (>5 sec)							
Target											
Benchmark											
Ideal Value											

Figure 5-1 Functional Metrics Chart

5.3 Pick and Place Test

5.3.1 Equipment

- Arduino
- Resistors
- Wires
- Laptop
- 3D printed component to fit force sensing resistors
- 2 Force Sensing Resistors
- Stopwatch
- Battery

5.3.2 Variables

Dependant Variable:

1. Voltage achieved from the Force Sensor Resistors.
2. Time for the device to come to standstill.
3. Internal positional data.

Independent Variable: The only setting which will be changed is the force of the gripper. Currently, it can be programmed to actuate with a force of 0 – 40 Newtons.

Control Variable(s): To prevent deviation from the arm operating, a system file has been created. Within the system file the operating conditions of the robotic arm have been programmed. This will ensure that during all tests the same movement speed, acceleration, and force threshold before activating an emergency stop will be constant.

5.3.3 Method

To collect the data, a simple pick and place activity with an instrument containing FSRs will be used. The cobot's working speed, operating force (0 – 40 Newtons, with 5 N intervals) and payload will be calibrated and programmed. Additionally, four variable names will be generated: Start_Pos, Pick_Pos, Travel_Pos, and End_Pos. Using the cobot internal clock a timer will be generated before executing the program.

Starting from the Start position (Start_pos), the cobot will move to pick up the component (Pick_Pos). The cobot will then move to the travel position (Travel_Pos) before reaching the (End_Pos) to finally place the component and return to the start position (Start_Pos). Throughout the program, the time to complete the activity will be recorded and at each 'Position' the program will display it's co-ordinates as a recorded variable.

Ultimately, this test will allow the program run time, and the time to reach each stage to be determined. The FSR's will show a peak force when the component is picked, followed by any deviation during the arms movement to the (End_Pos) when the component will be placed. It is expected a force time curve will be generated. Using the force time curve, and the programmed data, it should be possible to match each step to the part of the curve.

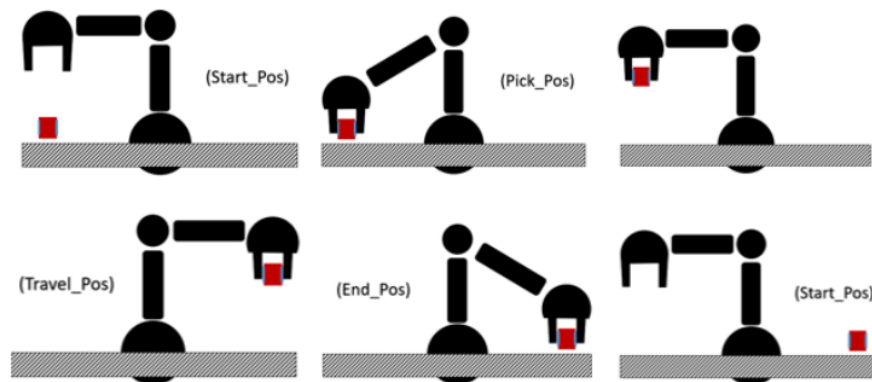


Figure 5-2 Testing Positions

6 Results

“Insanity: doing the same thing over and over again and expecting different results.” – Albert Einstein

6.1 Funding Challenges

Equipment and consumables were required to be purchased, however, in February 2024 the project management team issued a Work Instruction (WI) to cease all further procurement. Ultimately, due to limited funding there was a freeze to procuring the test equipment and no tests could be achieved for the financial year 2023 /24. As a result of the WI, assurance testing for the project has been re-assessed and financially planned and secured for the financial year 2024 / 25.

The longer term impact of the WI has also restricted the procurement of future platforms. This will lead to a reduced pace at developing SQEP within Dstl, additionally, the risk to explosive workers processing explosive activities will remain constant. As a result of minimal development and testing activities to achieve (semi)-autonomous remote working.

Overall this impact has been raised and the roadmap has been updated for the investigation of future collaborative robot devices.

6.2 Data Collected

Using the tools available within the lab, a minor experiment was conducted. The objective was to record the time for the gripper fin tips to fully open and close. The dependent variable remained the same (change of Force settings for the gripper). Table 6-1 and Figure 6-1 displays the results.

Force (N)	Time (S)
40	1.1
30	1.3
20	2
15	2.8
8.5	8.5
3	10.5

Table 6-1 Gripper Actuation Time Results

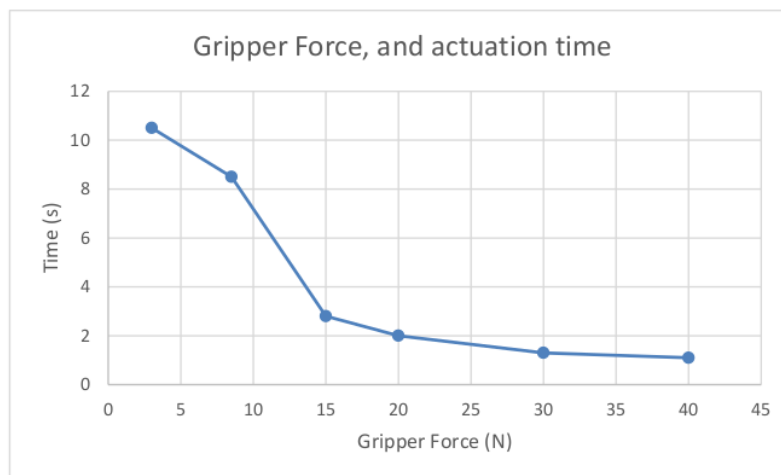


Figure 6-1 Gripper Force and Actuation Time Graph

6.3 Future Steps and Predictions

Future steps are to execute the pick and place experiment with a Force Sensing Resistor (FSR). By conducting this test the programmed force of the gripper can be compared to the exerted force onto the component. There is predicated to be two sets of data observed from the FSR: An impact force, and a frictional force.

1. Impact Force: Based on the gripper force, and actuation time chart it is predicted that a similar chart will be generated (Figure 6-2). If the fingertips are programmed at a greater force, the time to actuate will be less. Therefore, it is hypothesised there would be a greater peak pressure detected by the FSR over a shorter time.

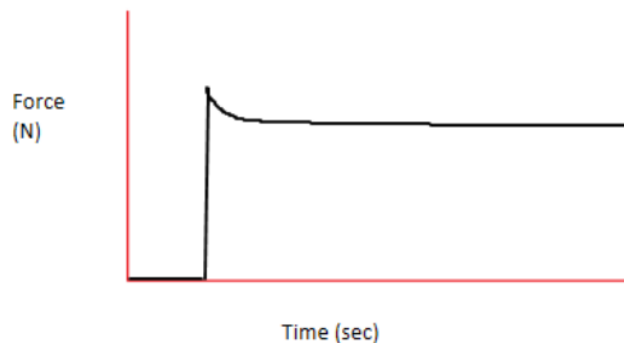


Figure 6-2 Predicted Force Time Curve

2. Friction Force: Once the component has been secured between the fingertips, the arm can begin to lift the component. Using the FSR it is predicted of a near-constant applied force over the duration of the time (Figure 6-2). The force keeping the component within the fingertips is predicted to be a combination of compression force, and friction due to gravity. It is currently unknown if there is a sweet spot for applying a set mechanical force to secure the component. If the gripper force is less, it is predicted

impact time would be less. However, since the fingertips are applying a lower force it is predicted there would be a lesser compressional force to secure the component and greater frictional force.

No experimental considerations have been made yet for lifting the component at an angle to reduce frictional force and apply weight to the arm.

Using both data types (Impact Force, and Friction Force), the values were then going to be compared against primary explosive small scale hazard testing. As primary explosive are the most sensitive, compared to secondary explosives, if it can be determined that the cobot can handle primary explosive substances then this data can be used to reason the cobot poses the ability to handle secondary explosives.

Overall, based on the data from Figure 6-1 and Table 6-1 it is predicted the cobot working at lower forces would reduce compression, and impact however pose a risk of increasing frictional force. Future research is to determine if a force setting and actuation time can be set independently of each other. Allowing a greater applied force over a longer set time period, reducing the impulse.

7 Discussion

*“The aim of argument, or of discussion, should not be victory
but progress.” – Joseph Joulbert*

Unfortunately, due to the lack of results, an argument for the use of a cobot to process energetics, backed by quantitative data, cannot be made. However, what can be achieved is the following:

1. An evaluation of the UR3e against the product specification.
2. An evaluation of the pick and place test to ensure data relevance.
3. Identification of potential use cases and next steps.

7.1 UR3e Evaluation

Based on the product specification achieved in QFD 1, and the system Pugh the UR3e arm does not meet all criteria. An argument could be made that since the device is not ATEX-rated, does not have in-built vision, Lidar, or infra-red sensors that it should have not been procured as it does not meet the requirements. Especially since adhering to explosive regulations was considered a critical requirement.

However, it should be noted that the procurement of the cobot arm was accomplished before a systems design approach was undertaken. As such the critical features to base the procurement decision was not present at the time.

The procurement of the arm was justified due to Universal Robots (UR) being perceived as the market leader. This was due to their products being able to integrate into Machine Learning, CAD, and Computer Aided Manufacturing softwares. As a result, the procurement of the UR model would allow more research and development pathways to build SQEP and knowledge of system deployment.

Overall, the current UR3e does not meet the mission statement criteria, but, it does enable the development of SQEP and test. The testing of the UR3e enables the UR family tree to be tested, and allow users to build judgement on how to deploy the technologies, and identify what components would need to be procured to authorise the device to be implemented into an energetic environment.

7.1 Evaluation of the pick and place test

The experiments aim was to capture impact and friction data to evaluate against small scale hazard data. This would enable the authorisation of handling primary explosive substances based on quantitative data. The test was to replicate the data captured from Rotter dam testing (Impact data), and the BAM Friction tests (Friction data). However, it could be argued this data is not necessary as the device should be handling energetic components and not substances. As a result of the component, the primary explosive should have a minimal level of protection which may reduce the risk of accidental ignition.

Despite the potential use-case reducing the chances of direct handling of energetic composition, the data captured from impact slightly resembles the data from the Rotter Dam test. The Rotter Dam test involves dropping a weight onto an energetic material and finding the mass where there is a 50% chance of a reaction. Using a pressure time curve, control measures can be implemented to ensure the force of grasping an item does not exceed the dropped mass 50% ignition chance. Therefore, safety can be built into the system to prevent accidental ignition from impact.

BAM Friction tests use a porcelain pin and dish which are rubbed against each other to create friction. Mass is added to the spigot to increase the friction resistance. When signs of a reaction are present, the mass is recorded to determine friction sensitivity. In terms of relevance to a gripper, to hold a component a compressive force is applied in the jaws, and the frictional force prevents the component from slipping. During the handling of the instrument during the test in Chapter 6 the compressive force would be measured not the frictional. Additionally, the test conducted is unlikely to have similar co-efficient of

friction compared to the BAM Friction tests due to material, and surface area. Overall, more research and a re-evaluation is required to determine the frictional forces applied by the gripper to compare against frictional small scale hazard data.

Overall, during the review, it has been indicated that the impact data collected from the experiment will have relevance to review against small scaled hazard data. However, a new method is required to determine the friction of the gripper to enable a comparison of small scale hazard data.

7.2 Use Cases and next steps

An activity in which has been identified for the use of the cobot arm is for the operation of bullet pulling. Working with a remote hydraulic press the cobot arm could load, and unload weapon cartridges into the press to be pulled apart. Once the bullet is removed from the cartridge the arm can follow a set path to dispose of the propellant from within the cartridge.

By pivoting the mission statement from:

“Using a cobot, safely pick and place energetic components.”

To:

“Using a cobot, and a remote press, automate the process of bullet pulling (5.56 mm to 30mm)”

This in turn creates a specific task for the cobot which may engage the stakeholders as there is a physical product to assist with an activity. The new mission statement will then also allow the development of RAS technologies

communicating and working together. Additionally, for ammo boxes which require processing, the cobot has achieved a low-level repetitive task.

It is proposed a new market survey is conducted to determine ATEX available collaborative robots which involved Dstl's Explosive Safety Representative, Explosive Workers, and the Energetic Enclosure Facility Manager. This is to improve the likelihood of approval to use the equipment within a processing facility.

Overall due to the ambiguity in the mission statement it has led to a solution which is unlikely to be deployed in an energetic environment, however, it can be used for inert research and development.

8 Conclusion

"What feels like the end is often the beginning" – T.S Eliot

1. Testing is still required to be undertaken on the cobot arm to determine if the Universal Robots products are suitable to work with energetic materials. However, from background research, and the use of higher hierarchical controls it can be suggested that the use of Cobots can improve safety by achieving remote working.
2. It is strongly advised to improve stakeholder management by identifying a use case for a cobot. This would enable the project team to develop cobot solutions in-house and develop SQEP in terms of: knowledge of the system, and what considerations need to be taken to deploy the solution.

Overall, it is recommended for next financial year, a cobot use case should be identified. This will then develop experience gaining authorisation and permission to deploy potential solutions. Otherwise future research and development work is at risk of being conducted but not implemented.

9 Reflection

"It's on the strength of observation and reflection that one finds a way. So we must dig and delve unceasingly" – Claude Monet

9.1 Project Management Reflection

The original project timeline can be seen in Figure 9-1, while the actual timeline can be seen in Figure 9-2. There was an optimistic view at the beginning of the project that it would be completed in October 2023. This was not the case. During the procurement of equipment there were challenges with commercial, additionally, an unexpected lead time to the procurement of equipment. Once the product was received it was determined some components were defective and had to be returned to the supplier in Denmark. This pushed majority of the deliverables right. During which other external influences in terms of work opportunities crept up and took priority over the final year project. Ultimately, these opportunities distracted progress from the final year project in which the spending freeze Work Instruction negatively impacted the overall program unexpectedly.

		Week Commencing																																																
		Month 1							Month 2							Month 3							Month 4							Month 5							Month 6							Month 7						
		03-Apr-23	10-Apr-23	17-Apr-23	24-Apr-23	01-May-23	08-May-23	15-May-23	22-May-23	29-May-23	05-Jun-23	12-Jun-23	19-Jun-23	26-Jun-23	03-Jul-23	10-Jul-23	17-Jul-23	24-Jul-23	31-Jul-23	07-Aug-23	14-Aug-23	21-Aug-23	28-Aug-23	04-Sep-23	11-Sep-23	18-Sep-23	25-Sep-23	02-Oct-23	09-Oct-23	16-Oct-23	23-Oct-23	30-Oct-23	31-Oct-23																	
No.	Activity																																																	
1	Project Management																																																	
1.1	Reporting To Work Package Lead																																																	
1.2	Weekly Journal Entry	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																	
2	Install Equipment																																																	
2.1	Training																																																	
2.2	Equipment Risk Assessment	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																	
2.3	Safe working Methodology	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																	
2.4	PAT Testing, and Installation	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																	
3	Develop Testing Environment																																																	
3.1	Research, and planning						X	X	X	X	X	X	X	X	X	X	X	X																																
3.1.1	Energetic Requirements																X	X																																
3.1.2	Regulatory Requirements																																																	
3.1.3	Operational Requirements																																																	
3.2	Develop Testing Environment																	X	X																															
3.3	Review Testing Environment																			X	X	X																												
4	Conduct Cobot Testing																																																	
4.1	Force Sensing Testing																							X	X	X																								
4.3	Result Analysis																									X	X																							
5	Documentation																																																	
5.1	Project Report																											X	X	X	X	X	X																	
5.2	Robotics Awareness Presentation																			X	X																													
5.3	Robotic Testing Results Presentation																												X	X																				

Figure 9-1 Initial Project Proposal Timeline

From the project management perspective it was learnt:

- **Not all threats can be seen.** Sometimes there are unknown unknowns which can negatively affect a project. Trying to plan for them all is foolish, however, developing a plan A, B, and C can save a project in a sticky situation.
- **Stakeholders need a gentle but firm push in the right direction.** As mentioned in Chapter 4.1.1 stakeholder management can help, or break a product design. It is crucial to engage effective stakeholders, and re-consider in-effective stakeholders as they could potentially lead to negative, and costly research and development.
- **Promising ahead of the deadline is a mistake.** Next time the project will be separated into the full timeline to prevent overpromises and under-delivery with space for challenges or unexpected delay to schedules.

9.2 Technical Reflection

9.2.1 Product Design:

Upon reflection the mission statement for the brief is too general. To improve both the development of experiments, stakeholder engagement, and product design a use case is required. While it has been beneficial to develop SQEP experimenting and developing programs with the cobot, it is felt faster development could be achieved with a use case. This in turn could then improve stakeholder engagement as they would be receiving a product which then could implement. There is arguments that before it is considered deploying a device SQEP needs to be built. Otherwise if the device is not successful then robotics in energetic environments will not expand. The counter argument is that devices are already

in the commercial world and have proven themselves. By developing and implementing products SQEP will be built faster than analysing, and then implementing.

9.2.2 QFD Experience:

It is strongly advised to utilise the QFD process for more projects. During the project QFD has been highly effective in identifying requirements, specifications and the development of tests. The process is time-consuming, however it is an effective design tool. Next time, it is advised to spend more time into market research before approaching SME to discuss their requirements. This would then aid the host during the meetings in which they will be able to help the SME's develop their requirements which aligns with current technologies, and also identifies areas which cannot be achieved. Overall, by conducting market research the host of the meeting with SME's can aid the discussion to develop relevant and critical requirements based on market designs.

10 References

- [1] GOV.UK, "The Defence Science and Technology Laboratory (Dstl) is the science inside UK defence and security.," Dstl, 01 January 2024. [Online]. Available: <https://www.gov.uk/government/organisations/defence-science-and-technology-laboratory/about>. [Accessed 14 March 2024].
- [2] Dstl Secretariat , "Accidents and or security breaches involving biological agents, nerve agents, gases or any other lethal chemicals at Porton Down from January 2014 to date," 11 April 2018. [Online]. Available: <https://assets.publishing.service.gov.uk/media/5b1fd2c3ed915d2cc380166d/2018-04111.pdf>. [Accessed 14 March 2024].
- [3] Health and Safety Executive, "Crown Censures taken by HSE since 1 April 1999," Health and Safety Executive , 11 July 2022. [Online]. Available: <https://resources.hse.gov.uk/convictions/documents/crowncensures.htm>. [Accessed 17 March 2024].
- [4] F. Sherwani, M. M. Asad and B. Ibrahim, "Collaborative Robots and Industrial Revolution 4.0," in *International Conference on Emerging Trends in Smart Technologies (ICETST)*, International, 2020.
- [5] S. Nahavandi, J. Mullins, M. Fielding, H. Abdi and Z.Najdovski, "Countering Improvised Explosive Devices through a Multi-Point Haptic Teleoperation System," in *International Symposium on Systems Engineering (ISSE)*, Rome, 2015.
- [6] S. Narayanan and C. Reddy, "2015," *International Journal of Engineering Research and Technology (IJERT)*, vol. 04, no. 02, pp. 89-93, 2015.
- [7] KLM Technologies Inc. , "Development of Robotics Applications in a Solid Propellany Mixing Laboratory," AFAL Technical Service Office, California, 1988.

- [8] A. Bonchis, E. Duff, J. Robers and M. Bosse, "Robotic Explosive Charging in Mining and Construction Applications," *Transactions on Automation Science and Engineering* , vol. 11, no. 1, pp. 245-250, 2014.
- [9] Youtube, "Robot Dog Help Workers on an Oil Rig," Reuters, 16 Nov 2020. [Online]. Available: <https://www.youtube.com/watch?v=PxgaYr5zFiY>. [Accessed 15 March 2024].
- [10] S. Stavinoha, H. Chen, M. Walker, B. Zhang and T. Fuhlbrigge, "Challenges of Robotics and Automation in Offshore Oil and Gas Industry," in *International Conference on Cyber Tecnology in Automation, Control and Intelligent Systems*, Hong Kong, 2014.
- [11] M. Wolinski, "Industry 4.0 and Explosion Prevention," *Fire and Environmental Safety Engineering*, vol. 247, p. 6, 2018.
- [12] E. Demaitre, "UR Injection Molding Machine INterface to help plastic manufacturers integrate cobots," 23 April 2020. [Online]. Available: <https://www.cobottrends.com/injection-molding-machine-interface-helps-integrate-ur-cobots/>. [Accessed 16 March 2023].

11 Bibliography

- [13] G. Fantoni, M. Santochi, G. Dini, K. Tracht, B. Scholz-Reiter, J. Fleischer, T. K. Lien, G. Seliger, G. Reinhart, J. Franke, H. N. Hansen and A. Verl, "Grasping devices and methods in automated production processes," *CIRP Annals*, vol. 63, no. 2, pp. 679-791, 2014.
- [14] W. Drotning, W. Wapman and J. Fahrenholtz, "Safety Issues in Robotic Handling of Nuclear Weapon Parts," Sandia National Laboratories, Albuquerque, 1994.
- [15] O. Tavsels, "MECHATRONIC DESIGN OF AN EXPLOSIVE," Engineering and Sciences of Izmir Institute of Technology, Izmir, 2005.
- [16] D. Y. Igor Nevliudov and L. Ivanov, "Analysis of the state of creation of robotoci complexes for humanitarian demining," *Information and Control systems: Systems and control processes*, vol. 6, no. 62, pp. 47-52, 2021.
- [17] E. Mitka, A. Gasteratos, N. Kyriakoulis and S. G. Mouroutso, "Safety certification requirements for domestic robots," *Safety Science* , vol. 50, no. 9, pp. 1888-1897, 2012.
- [18] T. C.Looney, A. G. Milligan, D. P.Perno, N. M. Savard, M. Scalise, G. T.Teran and R. I.Wheelock, "Origami Robots for Explosive Ordnance Disposal," Worcester Polytechnic Institute, Worcester .
- [19] D. Pham and S. Yeo, "Strategies for Gripper design and selection in robotic assembly," *Int. J Prod. Res* , vol. 29, no. 2, pp. 303-316, 1991.
- [20] A. M. Angulo, L. P. Pinto, E. S. Espinoza, Y. S. Vidal and E. S. Colquehuanca, "Assisted Operation of a Robotic Arm Based on Stereo Vision for Positioning Near an Explosive Device," *Robotics* , vol. 11, no. 100, pp. 1-18, 2022.
- [21] J. Hernandez, M. S. H. Sunny, J. Sanjuan, I. Rulik, M. I. I. Zarid, S. I. Ahamed, H. U. Ahmed and M. H. Rahman, "Current Designs of Robotic

Arm Grippers: A Comprehensive Systematic Review," Robotics , vol. 12, no. 5, pp. 1-33, 2023.

- [22] D. M.Chubb, "Exchangeable End Effectors for the Army Explosive Ordnance Disposal (EOD) Robot," Virginia Polytechnic Institute and State University , Blacksburg , 1993.
- [23] United Nations, "Manual of Tests and Criteria," United Nations Publication, New York and Geneva, 2019.
- [24] J. A. Conkling and C. J. Mocella, Chemistry of Pyrotechnics Basic Principles and Theory, Boca Raton : CRC Press Taylor's & Francis Group, 2019.
- [25] Defence OME Safety Regulator, "DSA 03.OME Part 2 (JSP 482) - Defence Code of Practice (DCOP) and Guidance Notes for In-Service and Operational Safety Management of OME," Nov 2019. [Online]. Available:
https://assets.publishing.service.gov.uk/media/5ee8b1a986650c03f0a4304a/DSA_03_OME_PART_2_JSP_482_CH_08__Nov_19_-_mod_gov_uk.pdf. [Accessed 15 March 2024].
- [26] L. Simpson and M. F. Foltz, "LLNL Small-Scale Friction Sensitivity (BAM) Test," US Department of Energy, Oak Ridge, 1996.
- [27] M. Weaver, L. H. Blair, N. Flood and C. Stennett, "A review of the Mallet Impact Test for Small Scale Explosive Formulations," Centre for Defence Chemistry, Cranfield University, Shrivenham.

[illegible]

57

Appendix B Quality Function Deployment

How	Importance	Robot Arm Functions											End-effector Functions					Functions for both																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									
		Program	Simulate Program	Display Errors	Display workpiece	Control operating temperature	Monitor chemical reactions	monitor local environment	Equip tools	Verify position	Move	Place	Pick	Verify gripped component	Locate Work piece	Detect forces	Emergency stop	Control speed																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									
Requirements		1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

20240321_Evaluation_Of_Collaborative_Robots_V1.1

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Please ask Jenni Steen for your marking sheet for feedback.

75/100

PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8

PAGE 9

PAGE 10

PAGE 11

PAGE 12

PAGE 13

PAGE 14

PAGE 15

PAGE 16

PAGE 17

PAGE 18

PAGE 19

PAGE 20

PAGE 21

PAGE 22

PAGE 23

PAGE 24

PAGE 25

PAGE 26

PAGE 27

PAGE 28

PAGE 29

PAGE 30

PAGE 31

PAGE 32

PAGE 33

PAGE 34

PAGE 35

PAGE 36

PAGE 37

PAGE 38

PAGE 39

PAGE 40

PAGE 41

PAGE 42

PAGE 43

PAGE 44

PAGE 45

PAGE 46

PAGE 47

PAGE 48

PAGE 49

PAGE 50

PAGE 51

PAGE 52

PAGE 53

PAGE 54

PAGE 55

PAGE 56

PAGE 57

PAGE 58

PAGE 59

PAGE 60

PAGE 61

PAGE 62

PAGE 63

PAGE 64

PAGE 65

PAGE 66

PAGE 67