Cost-Benefit Analysis

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Abstract

The content of this report assesses the costs and benefits of Warwick Mobile Robotics' (WMR) most recent design, Cyclone. The 2015/16 team have improved upon the previous year's design, taking a unique approach to the design and build of an Urban Search and Rescue (USAR) robot; the modular design allows for quick assembly, disassembly and repair.

2015/16 costs totalled £43,761.97, 26.4% less than last year's spend. The costs associated with Cyclone have been split into four sections; raw materials (£312.66), components (£2,893.51), external manufacturing (£216.30) and labour costs (£40,339.50). In addition, three opportunity case studies are evaluated and discussed. This, crucially, includes a justification for the build of a new robot, as opposed to the continuation of last year's, to ensure the longevity of the design.

Furthermore, the project was deemed to benefit the team, academia, the University, education and society. The 100 hours of volunteering outreach carried out by the team, which aimed to inspire the next generation of engineers into the field of robotics, was validated by the increased website traffic accrued after each event and articles written about the project.

Ultimately, the WMR project has been a worthwhile endeavour. The high expense incurred with a project of this nature is greatly outweighed by the benefits it brings. The potential to stimulate a commercial USAR robot that, when in operation, could save even one life, would make the project worthwhile.

Declaration

We, the authors, hereby declare that the work presented in this document, relating to "Next Generation Urban Search & Rescue Robotics," is entirely our own, in partial fulfilment of Academic Deliverable ES410 Group Project.

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Technicians **Research Assistants**	At both WMG and the School of Engineering for sharing their technical knowledge and assisting with manufacture.
Margaret Low	Who gave us the opportunity to inspire the next generation of engineers and programmers.
Scott Flower **Ben Green** **Mark Gibbons** **Chris Partridge**	For their assistance in the selection of critical components of the robot build.
Sponsors	WMG, the School of Engineering, Harwin and Maxon Motor for their continuous support.

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1 Introduction

The WMR 2015/16 team have created a new USAR robot, Cyclone. Cyclone has been developed with the capability to traverse through a disaster zone and seek out survivors. The following report outlines the costs and benefits of the 2015/16 WMR project and discusses the relative merits of each.

2 Aims & Objectives

The aims of the 2015/16 project are:

1. To further develop upon the 2014/15 robotic vehicle design, improving its functionality and search and rescue capabilities as the second stage of a 4 year plan.
2. To provide a solid platform to the 2016/17 team for further development with the intent of competing at the 2017 *RoboCup* competition.
3. To raise awareness of the importance of rescue robotics and to inspire the next generation to enter the exciting world of engineering and programming.

In order to reach these aims the following objectives were created;

1. Carry out a critical review of Orion (2014/15 robot) to understand its functionality and determine which aspects will be redesigned and which will be carried forward, saving design and manufacturing time.
2. Ensure a fully functioning robotic vehicle is produced in order to act as a basis for the 2016/17 team, allowing for final additions to be incorporated in order to successfully compete at the 2017 *RoboCup* competition.
3. Raise awareness of WMR projects and create relationships between suppliers, the society and institutions.
4. To offer the younger generation the opportunity to gain insights into advanced engineering and technology through outreach events such as the *Imagineering* Conference.

3 Cost of Project

The total cost of the Cyclone project was £43,761.97, consisting of components, materials, external manufacturing and labour costs.

3.1. Materials, Components and Manufacturing Costs

The procurement of raw materials, required for the fabrication of many components, accounted for 0.71% of the total project cost. Purchases of commercial-off-the-shelf (COTS) components contributed a further 6.61% to the project's cost. The rationale behind using COTS components is discussed in Section 4. In some cases, such as the motors and tracks, functioning components required replacing to future-proof the robot and meet requirements with an appropriate factor of safety. WMG's internal ordering system, OPERA, was used to request the purchase of components. Project spending required internal appraisal before placing any orders. This system ensured that the team thoroughly assessed alternatives before orders were placed. By doing so, suppliers were selected based on merit, affordability and reputation. Breakdowns of the materials, components and external manufacturing costs are presented in Table 1, with a full breakdown including additional tools and fasteners presented in the appendices.

The remainder of the physical costs of the project were incurred in the realization of each part from the acquired materials; these costs are quantified through the labour required. Whilst evaluating material costs can be relatively straightforward, due to the small variation of materials across the design, appreciating the cost and required manufacturing time is somewhat more difficult given myriad processing options to choose from. The design, and in some cases redesign, had an impact on the options available, providing the team with the opportunities to reduce these costs through part-simplification and other means, elaborated on in Section 4.

Table 1: Breakdown of component, materials and external manufacturing costs

Section	Raw Materials	Components	External Manufacture	Sub Totals	
	Cost (£)	Cost (£)	Cost (£)	Cost (£)	% Total
Chassis	72.90	45.15	111.00	229.05	6.69
Drivetrain	84.85	1759.86	40.00	1884.71	55.08
Suspension	127.56	67.37	0.00	194.93	5.69
Dynamic Tensioning	27.35	233.66	0.00	261.01	7.63
Electronics	0.00	632.20	65.30	697.50	20.37
Communications	0.00	155.27	0.00	155.27	4.54
Sub Totals	312.66	2893.51	216.30		
Grand Total				**3422.47**	

3.2. Labour Costs

Inherent within a project of this nature, is the reliance on hundreds of man-hours from numerous involved parties. These hours, and their associated labour costs, are shown in Table 2. Whilst the WMR team itself drove the project from conception through the design phase and onto manufacture, other parties listed in the table proved invaluable throughout the project and success would not have been reached were it not for their input.

Table 2: Breakdown of Labour costs

Role	Cost/hr (£/hr)	Individual	Hours	Cost (£)
Student	15	Joseph Flannery	340.5	5107.50
		Harvey Francis	360.0	5400.00
		Maximilian Gloger	391.5	5872.50
		Alex Lamm	291.3	4369.50
		Yung-Yu Lau	367.0	5505.00
		Daniel Riley	402.0	6030.00
Technician	30	Carl Lobjoit	76.0	2280.00
		Darren Woon	2.0	60.00
		WMG technicians	2.5	75.00
		Ian Griffifths	3.0	90.00
		School of Engineering technicians	15.0	450.00
Project Director	75	Dr Emma Rushforth	50.0	3750.00
Other Academic	50	Peter Kimber	1.0	50.00
		Ken Mao	2.0	100.00
		Stefan Winkvist	3.0	150.00
		Edgar Zauls	3.0	150.00
Sponsors	50	Scott Flower (Harwin)	3.0	150.00
		Ben Green (Harwin)	3.0	150.00
		Mark Gibbons (Maxon Motor)	10.0	500.00
		Chris Partridge (TransDev)	2.0	100.00
		Total	**2327.8**	**40,339.50**

The time the WMR team has spent on the project to produce Cyclone can be broken down by system (Figure 1) and by work done (Figure 2). Although all members of the team had set responsibilities, these were not fixed; each member took responsibility for work on multiple systems ensuring a balanced workload.

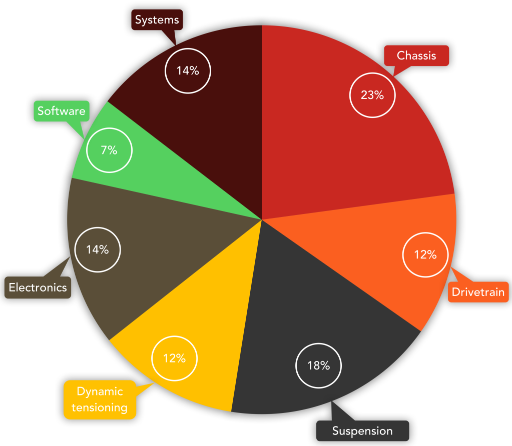

Figure 1: Breakdown of Team Time Spent per System

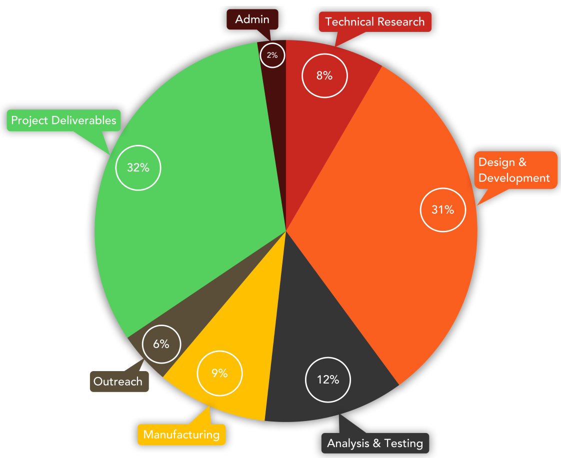

Figure 2: Breakdown of Team Time Spent per Category

3.3. Environmental and Social Costs

Often overlooked in academic projects are the associated environmental and social costs. These are of particular relevance for the WMR team, as an industrialised, in particular high volume manufacturing culture, is at least partly responsible for many of the disasters that may require a USAR robot. These disasters can be caused through the global warming potential of materials and processes, or the extortion of low-cost labour that has lead to a distaste towards the Western world. Through this lens, there is an argument to be made that the work of the WMR team is supporting the industries and mindsets that have led to the need for such approaches to begin with; the team have bought a variety of aluminium alloys for example, which require substantial energy inputs and generate a number of toxic wastes. It is imperative, therefore, that a positive impact is made by the project and the research carried out to ensure that the net impact is beneficial to the planet.

4 Opportunity Costing

4.1. The Cost of a Bespoke Processor

At the heart of Cyclone's electronics is its processor. This device drives the robot whilst collating sensory data, which is wirelessly fed back to the robot's base station. The criticality of this component dictated that the team undertake a thorough investigation to determine whether to purchase a commercial processor or to design and fabricate a bespoke board.

The design and manufacture of a tailored processor board would be beneficial to the project, as newer technology such as USB 3.0 and other high-speed I/O could be engineered into it. The new processing architecture could take advantage of innovative Field Programmable Gate Array (FPGA) devices, integrated with the processor, as they are suited to the video streaming and processing applications of Cyclone. These capabilities are currently lacking within COTS devices, but could be available in the future. This would limit the longevity of the processor if a pre-made board were purchased, in addition to the larger size and unnecessary features of a COTS board.

The building of a new processor would require extensive work, so much so that the total cost (including parts, labour and manufacturing) of the build would surpass that of a COTS product. Even with WMR leveraging its range of sponsors, it could not compete on price with large firms, who benefit from economies of scale. Traditionally, a board of this complexity would require multiple iterations of design, which increases both time and cost of the project. The culmination of cost and added complexity ultimately led to the team's decision to buy a COTS processor.

4.2. The Cost of Faster Processes

Where fabrication of components has been required, a choice of manufacturing processes has existed. Nowhere has this been more prevalent than the chassis' structural body, where bespoke components require extensive fabrication work; where parts interface, machined faces were required, often with tapped or clearance holes to join components together. Other components required depth changes to accommodate fixings, requiring further machining. These operations all represent a very real cost to the project in equipment, expertise and time. A decision, therefore, was required as to the means of manufacture for these components.

CNC machining technology would allow for most, if not all, of these activities to occur on a single machine, where tool changes and parts rotation can also be automated to further reduce labour costs. This results in a far reduced lead time and ensures that all features are relative to a common datum, difficult to achieve where different machines are used. Furthermore, part integration would be possible, reducing later assembly processes, however, to such machines and trained operators comes at a large cost.

The alternative to this is to use experienced machinists and manual processes. Near net shape could be achieved using quick and cheap water-jet cutting, which can then have interfaces machined flat and details added. This second method is far cheaper than the first, but requires significantly more time to achieve.

In this case, the benefits of selecting CNC machining would have far outweighed the costs, were the team to have foreseen the delays in manufacture. Considering the tight schedules and limited budgets of 4^{th} year projects, this decision can be the difference between a finished project and a collection of half-finished components.

4.3. The Cost of a new Design

When the 2015/16 WMR team started the Miniature Urban Search and Rescue (M-USAR) project in Autumn of 2015, the decision had to be made as to whether to bring Orion to a state where it could operate or whether it would be more advantageous in the long term to design and build a new robot. If Orion were further developed it is likely that the M-USAR project would be tied into the platform for several academic years, resulting in significant investment of both time and resources.

A critical analysis was conducted on Orion to determine the feasibility of developing the robot further. Benchmarking suggested that the design did not meet the required specifications. Most notably, Orion's motors were not powerful enough, nor was the chassis long enough, for it to climb stairs - a key requirement of the project. To enable Orion to meet these requirements, new, far-larger motors would be needed as well as extensive re-manufacture. This, along with the other limitations of Orion, made designing a new robot a more effective use of resources, providing a more flexible platform for future teams to develop upon.

Where possible, efforts were made to share and reuse components or designs to reduce costs. Several costly drivetrain components were carried over to Cyclone, such as the motor controllers and drive wheels. Existing designs were adapted for an increased track length and the suspension and tensioning systems were re-engineered.

There were costs associated with designing a new robot other than those of material and labour. A new design would hinder the team's chances of competing in the 2016 *RoboCup*. However, were the current robot sent to the competition, it would have not performed competitively, if at all, rendering the expense of the competition unjustified.

Overall, it was concluded that the benefits of designing a robot from scratch that would fulfil the criteria outweighed the costs associated with a new design.

5 Project Benefits

5.1. Benefits to the Team

The project has offered myriad opportunities for personal development, communication and team skills; the multi-disciplinary nature of the project has provided an invaluable insight into the type of work that team members will likely encounter in their future careers. Additionally, there have been opportunities for training in manufacturing processes such as drilling, tapping and media blasting. This has allowed the team to further develop a vital understanding of the manufacturing processes often used in industry.

The team have also dealt with a variety of suppliers such as Maxon Motor and Aquajet Profiles Ltd. This has provided the team members with an appreciation for lead times, costing and difficulties that are inherent when working with external suppliers; the team has had to adapt their project timeline to accommodate for these difficulties.

5.2. Benefits to Academia

The knowledge presented in previous WMR reports are often cited in other academic papers, proving the value of the work carried out. WMR projects are also contributing to research into USAR robots, which is essential since the onus of research falls mostly on academia due to the lack of commercial funding available.

5.3. Benefits to the University

Cyclone could also be used by the University of Warwick as a teaching implement, making learning more engaging and hands on. The robot could take pride of place at open days as an advertisement for the fascinating work carried out within the School of Engineering and WMG. The various outreach events attended each year act as invaluable publicity for the University, giving them a chance to entice not only new industrial sponsors but also prospective students.

This project benefits the University as its intent is to provide a solid base for the 2016/17 WMR team to develop and take to the 2017 *RoboCup*. The competition can showcase the University's work in mobile robotics on a world stage.

5.4. Benefits to Education

The team have attended outreach events to raise awareness of the world of robotics and its applications, particularly to the younger generation. These events have provided an insight into the potentials of robotics and has hopefully provided education on the benefits of pursuing a course related to the subject.

5.5. Benefits to Society

The WMR team will contribute to progress within the field of rescue robotics, leading to an advancement in the capabilities within the field. By entering global competitions WMR are contributing innovative ideas, which may be incorporated into the design of commercially available rescue robots.

Commercially available rescue robots would be utilised by rescue services to aid personnel in disaster zones. The robots would be deployed and remotely operated by a single person, removing the risk of sending emergency personnel into a dangerous environment. From a safe distance, the operator could send the robot into hazardous environments to map the area, locate potential survivors and provide aid to these survivors. They have the potential to be invaluable pieces of equipment to rescue services.

6 Outcomes & Achievements

6.1. Project Outcome

WMR aimed to design and build a modular robot platform that adheres to the specification set out by the *RoboCup*. The robot can be further developed by future teams to expand capability and enter into competitions with the aim of performing highly and surpassing previous results.

The 2015/16 team successfully designed and commenced manufacture of Cyclone. The framework has been set in place for the next team to complete the manufacturing and further the capability of Cyclone with the addition of a robotic arm and enhancement of the sensor array.

6.2. Sponsorship

The 2015/16 WMR team has further strengthened sponsorship relationships. Such relationships have resulted in contributions such as Harwin supplying connectors for the power distribution and battery monitoring board free of charge (total value, £367), whilst Maxon Motor gave a £546 price reduction on the motors. Maxon Motor also provided extensive assistance when selecting the motors, which was invaluable.

6.3. Publicity

As previously stated, the WMR team took part in several outreach events in 2015/16, including the *2015 Midlands Imagineering* Fair at the Ricoh Arena. These highlighted the importance of research into mobile robotics and engaged young engineers. The work of WMR at *Imagineering* was reported and published in the Coventry Telegraph (Figure 4). As part of WMR's outreach work, the team have participated in University open days to showcase the research conducted by the School of Engineering and WMG.

The WMR website has received 17,297 hits from the 6th October 2015 (start of project) to 24th

April 2016. The website statistics (Figure 3) show that here have been spikes in traffic after these events, particularly the *Festival of the Imagination* and *Imagineering*. There is significant interest in the work done by WMR, and this highlights the value of the work to those outside the University. The WMR website has seemingly become a resource as almost 10,000 past reports have been downloaded.

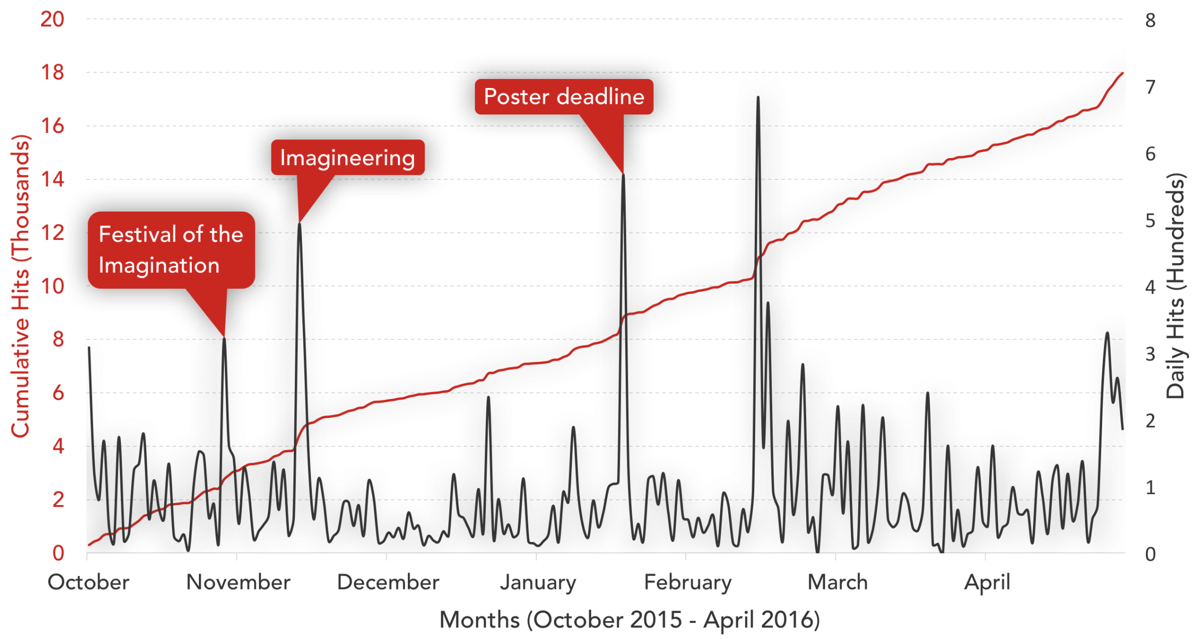

Figure 3: Cumulative and Daily Hits

Budding engineers flock to Ricoh event

Simon Gilbert
Chief Reporter
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BUDDING engineers flocked to the Ricoh Arena over the weekend to take part in the mammoth 'Imagineering' fair.

The two-day event was held in the Jaguar Exhibition Hall over Saturday and Sunday. Visitors were able to take part in a wide range of hands-on activities hosted by more than 30 exhibitors.

Activities on offer included model-making workshops, robots, 3D scanning, flight simulators, jet car design and Mecanno modelling. There was also a paper aeroplane master class and the chance for youngsters to use microscopes to look at their own cells.

Les Ratcliffe, head of community relations at event-sponsors Jaguar Land Rover, said: "We are delighted to sponsor the Imagineering Fair and show young people from across the Midlands how exciting and rewarding engineering careers can be.

"The automotive industry needs more young people to become engineers to help us develop more sustainable vehicles, engines and technologies and the industry has a huge range of career opportunities to offer."

Andy Gibb, managing director of the Ricoh Arena, said: "The Imagineering Fair is always a fantastic two days for youngsters and their parents because of the great range of inter-active activities which are organised to entertain a wide range of ages."

Bob Shanks, chairman of the Imagineering Foundation and organiser of the event, said he hoped the event would help to nurture the minds of the next generation of engineers.

He said: "There are plenty of activities to provide hands-on experience of the world of engineering.

"Excited youngsters have the opportunity to stretch their creative imaginations as well as experience at first-hand modern technology that will hopefully inspire them to become part of the next generation of engineers."

Imagineering is administered by the independent education charity the Imagineering Foundation and is staffed by volunteers with engineering knowledge.

It aims to introduce young people between eight and 16-years-old to engineering, science and technology through fun, hands-on activities and personal involvement.

The University of Wariwck's Max Million Gloger with his robot Pinky

Figure 4: WMR featured in the Coventry Telegraph [1]

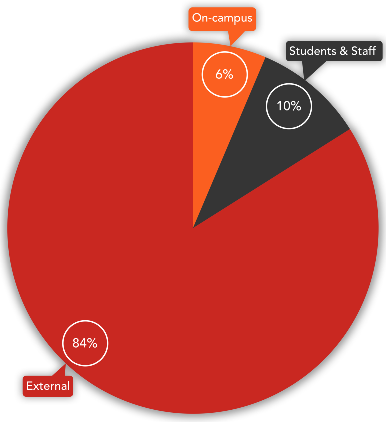

Figure 5: Pie Chart of Hit Location

7 Discussion & Analysis

7.1. Project Aims and Objectives

The 2015/16 team has achieved its aims stated in Section 2, by:

1. Reducing assembly times, maintaining or improving functionality and carrying forward components where appropriate from Orion.
2. Developing a modular robot, Cyclone, to future-proof the design and allow for subsequent teams to expand capability.
3. Attending outreach events and open days to publicise the work carried out by the research group and the 2015/16 team.

7.2. Cost Benefit Appraisal

The WMR 2015/16 project incurred a total cost of £43,761.97, compared with last year's £59,466.94, a 26.4% reduction. This reduction was achieved whilst simultaneously improving performance. Furthermore, components were reused where possible, at points, from the previous year. Ultimately, the costs incurred year-on-year, will continue to decrease whilst the benefits from the project, continue to rise in value, tangibly or otherwise. The net value of the USAR project, therefore, can be seen to appreciate.

Whilst the costs are explicitly stated, the benefits are less tangible. Attempts to calculate tangible benefits have been made where appropriate. The project has been appraised through it's functional outputs:

The newspaper article, featured in the Coventry Telegraph, reached approximately 61,000 readers throughout the greater Coventry area [2]. This increases awareness of the University's work, which directly feeds back into the University's prospective students as well as current students' future employers, ultimately increasing the value of obtaining a Warwick Degree. Positive publicity far outweighs the equivalent cost of an advertisement.

The 100 volunteer-hours committed to outreach events throughout the year, such as *the Festival of the Imagination*, consisted of the team members teaching younger generations about the potential uses of robots in the wider society. The equivalent teaching cost of approximately £1,500[1] is more than compensated for through the salaries of a few young, inspired engineers; this could total £2,000,000[2] of equivalent contributions to the field of robotics.

The cost of a human life has been estimated at anywhere between £1.6m [3] and £3.4m [4], though arguably it is priceless. Any impact that this project can have in reducing the time to victim discovery, and assistance in reducing fatality rates of both victims and first responders, during urban disasters is validation of the costs.

[1] Assuming our time is currently worth £15 per hour.
[2] Assuming they work for 40 years, earning an average of salary of £50,000.

7.3. Strategic Alignment

The School of Engineering outline their strategic vision in terms of research, teaching and industry. These, and the University's strategy, have been used as a means of appraising the work carried out by the 2015/16 WMR team.

The department aims to "pioneer new research areas that interface with other disciplines". The WMR project aligns well with this, as a result of the multidisciplinary nature of the project. This could, however, be furthered in the future by collaborating with, for example, the computer science department as their skill-set is directly applicable to WMR.

The University emphasises the importance of the economic, social and cultural benefits of its research. The USAR projects allow for this to happen, as they exist almost entirely for the benefit of society; in an urban disaster, all parties would benefit from the fast rescue of individuals. Further to this, the practical applications of robotics allow for the easy integration of WMR exhibits to various outreach events and ensure that the University's name is associated with research that positively benefits society.

Finally, the WMR team has contributed to the University's "Sustainable Cities" Global Research Priority, through the "risk, resilience and security" [5] theme. The team, which has displayed the work carried out at various outreach events across the year, has helped to publicise the realisation of these research goals to the general public, namely "planning for, detecting and responding rapidly to natural disaster" [6]. Returning to the *RoboCup* competition represents a future opportunity to further showcase the team's achievements towards these goals on the global stage, which will aid the University in justifying future funding.

8 Conclusions

The aim of this project, and similar projects completed by WMR teams, is to provide research and insight into the potentials of Urban Search and Rescue Robotics. The 2015/16 team put particular emphasis on the longevity of the design of Cyclone, ultimately spreading the cost over a number of years. Although successful, this project provided further proof of the difficulties in the advancement within the field of rescue robotics due to the large costs incurred and the lack of realised profit. The overall project cost this year, to begin the development of Cyclone, was £43,761.97 justified by the contribution it has made to the rescue robotics community. When compared to the cost of the 2014/15 project to build Orion, Cyclone came in 26.4% lower and showed significantly more progress in terms of the design of both mechanical and electronic systems. The overall project cost is warranted by its sole purpose of saving human lives, which arguably is a field that currently is overlooked due to its lack of commercial viability. If the 2014/15 and subsequent WMR teams can have just a small impact within the field of rescue robotics this will go a long way to the overall goal of increasing lives saved within disaster zones.

9 References

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10 Appendices

10.1. Chassis

Table 3: Chassis Cost Breakdown

Part	Supplier	Cost (£)
2mm Aluminium Plate (Material)	Colt	19.90
6mm Aluminium Plate (Material)	Colt	14.25
8mm Aluminium Plate (Material)	Colt	38.75
0.9mm Aluminium Sheet Cutting	Aquajet	4.00
6mm Aluminium Plate Cutting	AquaJet	22.00
8mm Aluminium Plate Cutting	Aquajet	85.00
Loctite 330 Liquid Acrylic Adhesive kit	RS Components	35.55
RS Blue chemical resistant gloves	RS Components	9.60
	Total	**229.05**

10.2. Drivetrain

Table 4: Drivetrain Cost Breakdown

Part	Supplier	Cost (£)
Tracks	TransDev	310.82
Motors, Gear and Sensor	Maxon Motors	1025.82
Motor Holders (Material)	Colt Materials Ltd.	33.00
Motor Holders (Material)	AquaJet	40.00
Bearings	IGUS	138.92
Bearing holders (Material)	Colt Materials Ltd.	40.00
Drive Axle (Materials)	RS Components	11.85
Gears	HPC Gears	37.20
Clamp Collar	RS Components	68.72
Washers	RS Components	7.54
Flange Bearing	IGUS	22.40
Collars	RS Components	68.72
Tandem Flange	RS Components	79.72
	Total	**1,844.71**

10.3. Suspension

Table 5: Suspension System Cost Breakdown

Part	Supplier	Cost (£)
Flanged Plain Bearings	IGUS	18.72
Thrust Washers - 5mm	IGUS	18.25
Thrust Washers - 10mm	IGUS	15.20
Thrust Washers - 15mm	IGUS	15.20
Bearing Blocks (Material)	Colt Materials	5.00
Blade Adapters (Material)	RS Components	11.05
Swing-arms (Material)	Aluminium Warehouse	6.31
Swing-arm Blocks (Material)	Revenance Ltd.	7.00
Torsion Blades (Material)	Colt Materials Ltd.	7.50
Tuning Blocks (Material)	Revenance Ltd.	6.90
Tuning Shoes (Material)	Revenance Ltd.	29.70
Aluminium Plate 1.5mm	Revenance Ltd	7.00
Aluminium Plate 3mm	Revenance Ltd	5.30
Aluminium Plate 4mm	Revenance Ltd	5.40
Aluminium Square 1"	Revenance Ltd	6.90
Aluminium Flat 1/2"	Colt Materials	5.00
Stainless T304	Colt Materials	24.50
	Total	**201.93**

10.4. Dynamic Tensioning

Table 6: Dynamic Tensioning System Cost Breakdown

Part	Supplier	Cost (£)
Springs	Lee Spring	71.02
Linear Bearings	IGUS	118.50
Rotational Bearings	IGUS	18.30
Thrust Washers	IGUS	17.60
Spring Caps (Material)	Colt Materials	15.50
Axles (Material)	RS Components	11.85
Loctite 380	RS Components	8.24
	Total	**261.01**

10.5. Electronics

Table 7: Electronics Costs Summary

Summary	
Part	**Cost (£)**
Battery Monitor Board	214.30
LED Board	2.40
Control	415.77
Manufacturing	65.30
Material Total	632.20
Manufacturing Total	65.30
Grand Total	**697.50**

Table 8: Battery Monitor Board Cost Breakdown

Part	Supplier	Cost (£)
Battery Monitor Board		
Microcontrollers	Onecall	22.11
5V Regulator	Powersolve Electronics	53.07
12V Regulator	Powersolve Electronics	88.68
USB Board	RS Components	7.39
Switches	RS Components	25.15
MOSFETs	Mouser	7.40
BJTs	Onecall	2.84
Fuses	Mouser	3.00
Resistors	Onecall	2.50
Capacitors	Onecall	1.35
Diodes	Onecall	0.81
Connectors	Harwin	FREE
	Sub Total	**214.30**
LED Board		
Green LEDs	Onecall	2.40
Connector	Harwin	FREE
	Sub Total	**2.40**
Control		
Battery Connector	Mouser	12.66
Processor Board	Impulse	403.11
USB A to USB B Cable	WMG	FREE
Connector Assemblies	Harwin	FREE
	Sub Total	**415.77**
Manufacture		
Battery Monitor Board	Euro circuits	55.30
LED Board Board	School of Engineering	10.00
	Sub Total	**65.30**

10.6. Communication

Table 9: Communication System Cost Breakdown

Part	Supplier	Cost (£)
Buffalo AirStation AC433 Wireless Travel Router	Buffalo via Amazon	34.99
ZyXEL NBG6503 Wireless Router	ZyXEL via Amazon	61.49
D-Link DWR-118 Wireless Router	Insight UK	58.79
	Total	**155.27**

10.7. Tools and fasteners

Table 10: Costs of tools and fasteners required

Tool/Fastener	Supplier	Cost (£)
Broach Set	GTSS Engineers Supplies	690.61
Tool Holder	MSC Industrial Supply Co	59.23
Inserts	MSC Industrial Supply Co	31.42
Optimal Centre Punch	Axminster	33.96
M3-M12 HSS Threading Set	Cromwell Tools Ltd	65.99
6mm 120 degree Spotting Drill	Cromwell Tools Ltd	10.93
Stainless Steel Socket Screw, M4 x 16mm	RS Components	8.44
Steel Zinc Plated Socket Screw, M5 x 35mm	RS Components	23.74
Zinc Plated Steel Washer, M6 x 25mm, 1.5mm	RS Components	2.67
Stainless Steel Nylon Insert Locking Nut, M5	RS Components	9.78
Stainless Steel Socket Screw, M6 x 10mm	RS Components	13.17
	Total	**950.24**

10.8. Hours Worked

Table 11: Breakdown of hours done by system

System	Hours	%
Chassis	246 2	22.85
Drivetrain	128 0	11.88
Suspension	191 5	17.78
Dynamic Tension	127 5	11.84
Electronics	152 0	14.11
Software	75 0	6.96
Systems	157 0	14.58
Total	**1077.2**	

Table 12: Breakdown of hours done by category

Category	**Hours**	**%**
Technical Research	144 0	8.27
Design and Development	541 2	31.08
Analysis and Testing	203 5	11.69
Manufacture	160 5	9.22
Outreach/External Events	98 0	5.63
Project Deliverables	552 6	31.74
Admin	41 5	2.38
Total	**1741.3**	