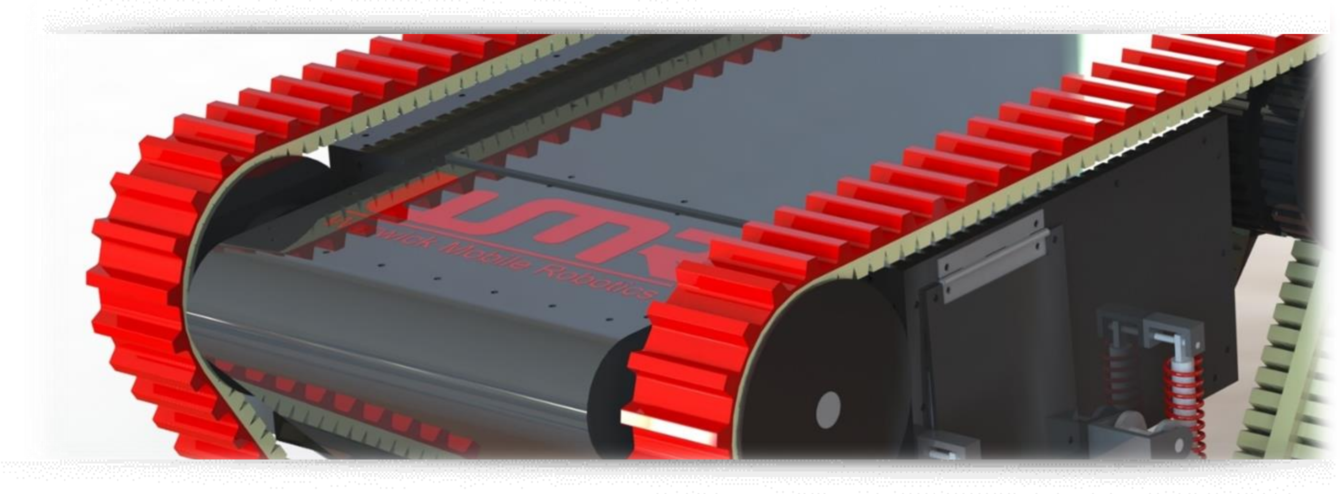

Urban Search & Rescue Robotics

Cost Benefit Analysis 2014/15

Authors:	0910923	1015945	1102283	1124745
	1114694	1117210	1117884	1124285

Sponsored By

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Acknowledgements

With many thanks to our supervisor, Emma, for keeping us on track (pun intended); to our technician, Carl, for making endless brackets and monitoring our designs; to all the technicians and staff in WMG and the School of Engineering, who were always ready to lend a helping hand; to Margaret for giving us the opportunity to help inspire the next generation of engineers with outreach projects; and to our sponsors: WMG, The School of Engineering, Transdev, MakerBeam and Maxon Motor, for all of their support.

Declaration

We hereby declare that this project work entitled "Urban Search & Rescue Robotics: The Design and Development of a Miniature, Urban Search & Rescue Robot" submitted to the University of Warwick, is the work done by Leigh Dawson, Craig Fox, Michele Galbusera, Paul Martin, Mara Nkere, Avnish Popat, Rebecca Saunders and John Strutton, under the guidance of Dr Emma Rushforth.

Authors:

Leigh Dawson

Craig Fox

Michele Galbusera

Paul Martin

Mara Nkere

Avnish Popat

Rebecca Saunders

John Strutton

Abstract

The Warwick Mobile Robotics (WMR) team has developed a new Mini Urban Search and Rescue (M-USAR) robot called Orion, which is designed to locate survivors in disaster zones. It demonstrates innovation and development in the field of robotics through advanced mobility, terrain handling and a modular electronic architecture.

The total cost of this project was £59,466.94, which consists of £4,082.94 of material costs and £55,384.00 of labour costs.

The key benefits of this project include a significant contribution to USAR research in the aim of saving lives, the knowledge and experience gained by students, academics and the wider society, the ability to inspire younger generations to study engineering and STEM subjects through outreach events and the enhanced supplier relationships obtained for future WMR teams and the University.

1 Introduction

The Warwick Mobile Robotics (WMR) team has developed a new Mini Urban Search and Rescue (M-USAR) robot called Orion, which is designed to navigate complex terrains in order to locate survivors in disaster zones. This Cost Benefit Analysis identifies WMR's achievements this year and provides justification for the costs incurred.

2 Aims and Objectives

The 2014/2015 aims:

- Deliver the mechatronic framework for an innovative M-USAR robot by May 2015 as the first stage of a three-year plan
- Provision for design development by future WMR teams
- Exhibit the robot as an educational platform to inspire younger generations

The following objectives provided guidance throughout the duration of this project:

- Analyse the design and functionality of current USAR robots and other multi-terrain vehicles
- Benchmark both of WMR's existing USAR robots to inform the design process
- Define an achievable specification for robotic performance complying with industry standards and RoboCup rules, by considering the results of benchmarking and previous robot strengths and weaknesses
- Design a mobile multi-terrain robot incorporating novel technology and innovative features to push the boundaries of established design by many teams and organisations
- Adapt the design for ease of manufacture, maintenance and safety
- Test components and features to validate the design against the specification, analyse capability in real world applications and identify progress and achievement by the 2014/15 team
- Document designs, provision for further work and a handover programme for future projects and developments
- Showcase the robot through technology conferences and exhibitions such as the Imagineering Fair 2014, media publicity and open days to promote engineering, robotics and other STEM subjects

3 Work Undertaken

In pursuit of delivering an innovative M-USAR robot, WMR have completed the following development stages: design, simulation, design for manufacture and assembly, manufacture, programming, assembly and testing. Orion, weighing approximately 25kg, is manoeuvrable in confined spaces and can be deployed by a single person. It is able to navigate difficult terrains with its high clearance and innovative suspension system.

3.1 Chassis and Shell

Extruded aluminium beam was used to construct a strong and highly adaptable chassis frame, shown in Figure 1. An aluminium shell encases the robot with multiple access panels to ensure easy access to the internal components, as shown in Figure 2.

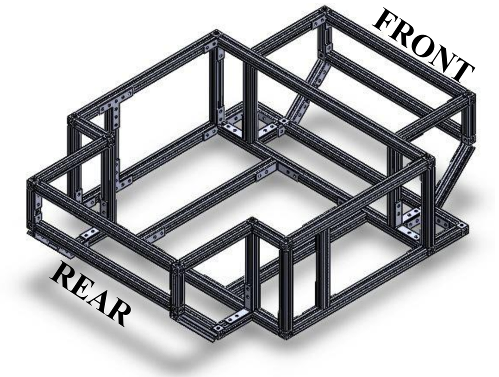


Figure 1: Chassis Design

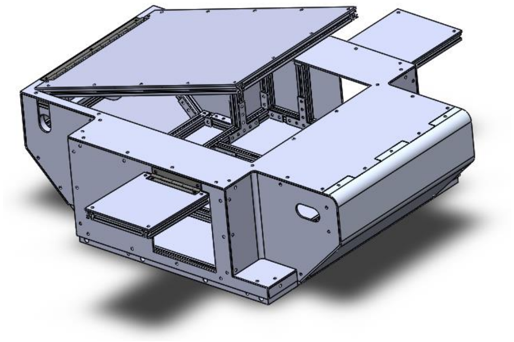


Figure 2: Chassis and Shell with Open Access Panels

3.2 Drivetrain and Suspension

A dynamically tensioned track design has been used to suspend the chassis above the ground, ensuring excellent clearance over obstacles. The tracks surround the body of the robot (shown in Figure 3) permitting movement whilst upside-down. The elevation of the chassis allows for the incorporation of an innovative suspension system (shown in Figure 4), enabling increased speed and mobility accuracy.

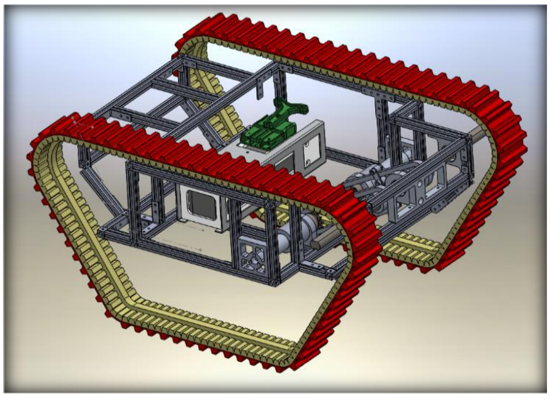


Figure 3: Track Layout Showing Chassis Suspended at 70mm

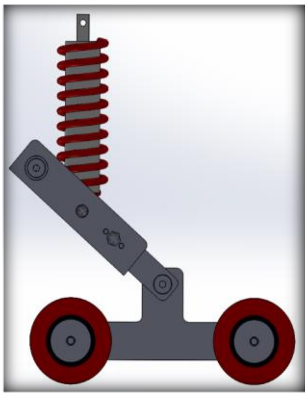


Figure 4: Suspension Assembly Design

3.3 Power Distribution

A compact power distribution board, designed based on analysis of previous WMR development, fits within the reduced chassis size. It has sufficient capacity to meet Orion's mechanical demands and has an additional factor of safety of 135%. This sophisticated design has a versatile and modular architecture and allows for further development. The final power distribution board is shown in Figure 5**:**

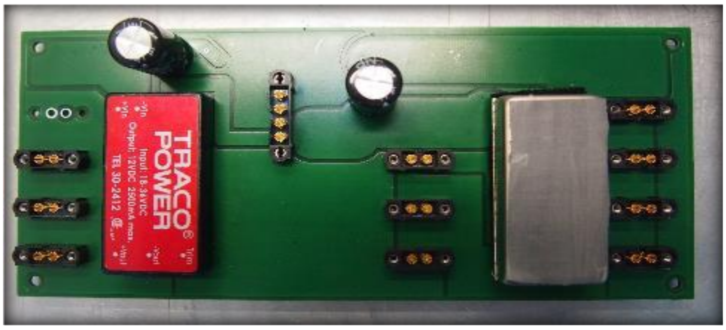


Figure 5: Final Power Distribution Board

3.4 Computing

The groundwork for Orion's core computing programs was created with the aid of the open-source Robot Operating System (ROS). Software programs have been created for the operation of the motors, the LiDAR, the CO_2 sensor and the cameras. Also, a network connection was established to allow communication between the WMG laptop and the robot.

3.6 Sensors and Mapping

A full sensory array design has been outlined for optimal tele-operated control and to provide capabilities essential for efficient identification of survivors. The power distribution has been designed to support these sensory components, all of which are integrated into the mechanical design. A schematic of the sensor layout is shown in Figure 6:

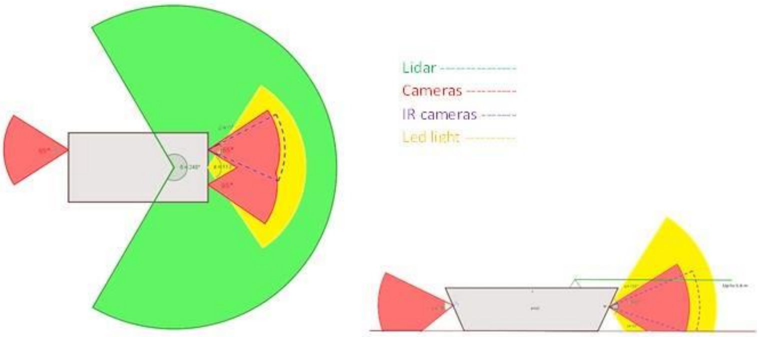


Figure 6: Orion's Sensor Design

The LiDAR is used to create a map of Orion's surrounding environment in order to identify the victims' location and establish accessible routes to them. Providing a 2D and 3D map is one of the scoring criteria of the RoboCup competition. The LiDAR model, Hokuyo URG – 04LX (Hokuyo Automatic, 2009), was used by previous years as it can detect objects up to 4 metres away and is also compatible with ROS.

3.7 Coherent Final Design and Manufacture

The above facets of design combine into a coherent mechatronic product. Figure 7 shows the final CAD design and Figure 8 shows Orion in the final stages of manufacture.

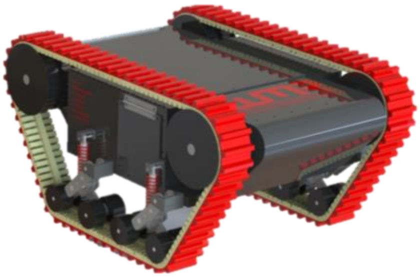


Figure 7: Orion Final Design

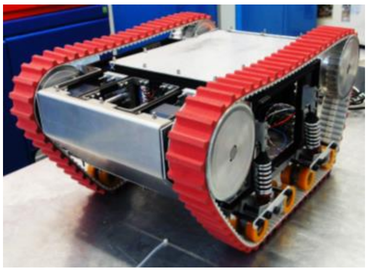


Figure 8: Manufacturing Orion

3.8 Testing

Component testing was conducted in order to ensure functional system operation and gauge the level of specification satisfaction. The components tested included the motors and the suspension dampers. The set-up for testing the stiffness coefficients of the suspension dampers is shown in Figure 9. Figure 10 shows primary manoeuvaribility testing, demonstrating how the suspension idlers adapt to the terrain.

Figure 9: Suspension Test Rig

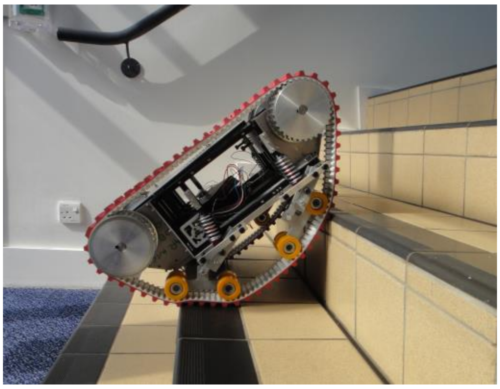


Figure 10: Primary Manoeuvrability Testing

4 Cost Benefit Analysis

4.1 Project Costs

The total cost of this project was £59,466.94 comprising of material, manufacturing and labour costs. Figure 11 shows a breakdown of the total costs by activity.

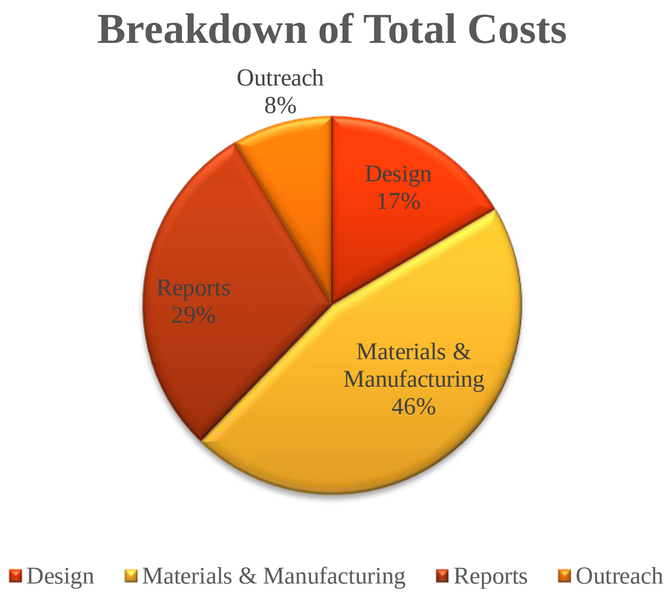


Figure 11: Breakdown of Total Project Costs

4.1.1 Material Costs

The total cost of materials and manufacturing amounted to £4,082.94. Table 1 shows the breakdown of the material costs by robot sub-system. These materials were purchased via the OPERA Purchasing System and the process involved is outlined is Appendix A.

Table 1: Material Costs by Sub-System

Component	Cost (£)	Percentage of Total Expenditure
Chassis	179.36	4.4
Shell	44.89	1.1
Drivetrain	2,565.91	62.8
Control Electronics	195.03	4.8
Sensors	73.74	1.8
Manufacturing	719.63	17.6
Miscellaneous	304.38	7.5
Total	**£4,082.94**	

4.1.2 Labour Costs

The WMR team have conducted the majority of the labour, with assistance from technicians during manufacture and support from both academic supervisors and sponsors. Table 2 shows the hours contributed by all individuals associated with the project.

Table 2: Breakdown of Labour Costs

Role	Cost/hr (£)	Individual	Hours	Cost (£)
Student	15	Avnish Popat	356	5340.00
		Craig Fox	355.5	5332.50
		John Strutton	357	5355.00
		Leigh Dawson	358	5370.00
		Michele Galbusera	340	5100.00
		Mara Nkere	345	5175.00
		Paul Martin	356.5	5347.50
		Rebecca Saunders	357.5	5355.00
Technician	30	Carl Lobjoit	253	7590.00
		Paul Johnson	5	150.00
		School of Engineering Technicians	4	120.00
Project Director	75	Dr Emma Rushforth	50	3750.00
Other Academic	50	Stefan Winkvist	10	500.00
		Edgar Zauls	10	500.00
Sponsors	50	Karen Whittaker (Maxon Motor)	3	150.00
		Paul Williams (Maxon Motor)	3	150.00
		Peter Mascoll (Transdev)	2	100.00
		Total	**3133**	**£55,384.00**

The team monitored individual hours spent on different tasks throughout the duration of the project and this breakdown of hours in shown in Figure 12.

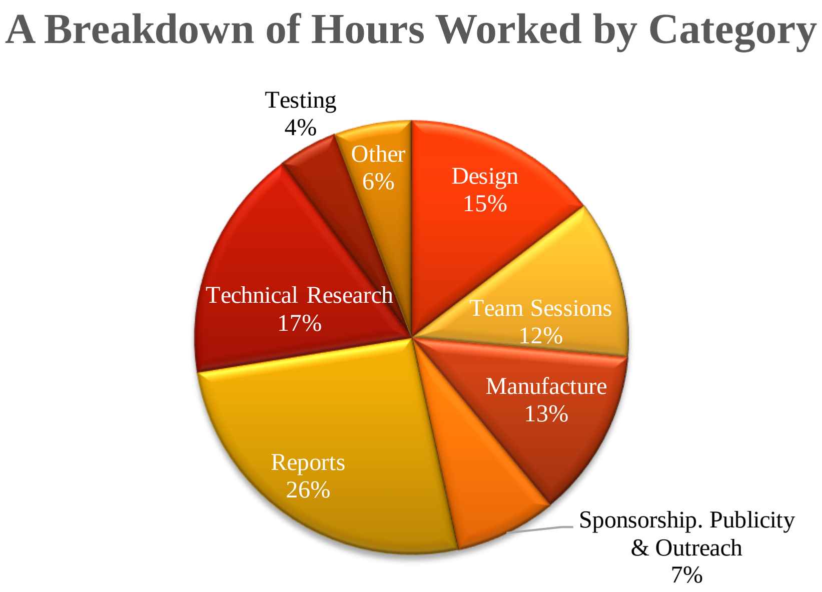


Figure 12: Breakdown of Labour Hours Worked by Category

4.2 Benefits

4.2.1 Benefits to Students

- Development of robotics skills and mechatronic design
- Experience of working within a multidisciplinary team
- Development of project management skills including time management, budgeting and finances
- Working and negotiating with suppliers and sponsors
- Product development with suppliers and experts in the field, such as Transdev
- An innovative, simple and effective robot design for development by future WMR teams
- Designing components for manufacture and reliability
- Development of practical engineering skills including use of CAD and machine tools

4.2.2 Benefits to Academics

- Relationships with suppliers and sponsors can be maintained for future projects
- New platform for further research in robotics
- Development can be used as academic material in Robotics based modules
- Promotion material for student recruitment brochures and an advert for the School of Engineering and WMG

4.2.3 Benefits to Wider Society

- Deployment of M-USARs such as Orion will reduce the risks to emergency service teams when searching for survivors
- The speed in which survivors can be found will increase as less time will be required to assess the safety and stability of the environment
- Time to survivor will also decrease due to reduced maintenance time (accessible and off-the-shelf components) and as a smaller vehicle it is manoeuvrable in confined spaces
- Published documents on the WMR website are available to other researchers for continued development in the USAR robotics industry and wider applications including bomb-disposal and nuclear decommissioning robotics
- WMR have encouraged the next generation to pursue engineering and robotics by taking part in Imagineering and providing open day demonstrations and other engineering events. In collaboration with Maxon Motors, Rebecca published an article titled "Women in Engineering" with the aim of encouraging young women to study STEM subjects.

5 Outcomes and Achievements

5.1 Learning Outcomes

In addition to the technical knowledge gained in the field of robotics, electronics and manufacturing, the following lessons have been developed:

1. Dealing with external suppliers – Working alongside suppliers has allowed the team to work with market specialists. However, being dependent on suppliers adds risk and hence the team has learned to generate contingency plans in order to mitigate this risk.
2. Coping with long lead times – The team has learned to prioritise tasks in order to cope with long manufacturing and lead times and ensure minimal disruption to progress.

5.2 Sponsorship and Publicity

This year WMR have worked alongside existing sponsors including WMG, the School of Engineering, Maxon Motor, MakerBeam and Transdev. In addition to providing monetary assistance, Maxon Motor has been essential to WMR's publicity this year; they have assisted in the publishing of project articles on several websites including Eureka (Fryer, 2015) and other engineering trade magazines, the publishing of Rebecca's "Women in Engineering" article (Maxon Motor, 2015) and the production of a team video-interview.

WMR have used Facebook as an outlet to keep those interested up to date with project progress. Figure 13 plots the post reach (number of people who viewed Facebook page posts) over the project year. Peaks in interest arose when WMR attended the 2014 Imagineering Fair, attended the 2015 Warwick Technology conference and were visited by Maxon Motor. The total post reach over the project year was nearly 8000.

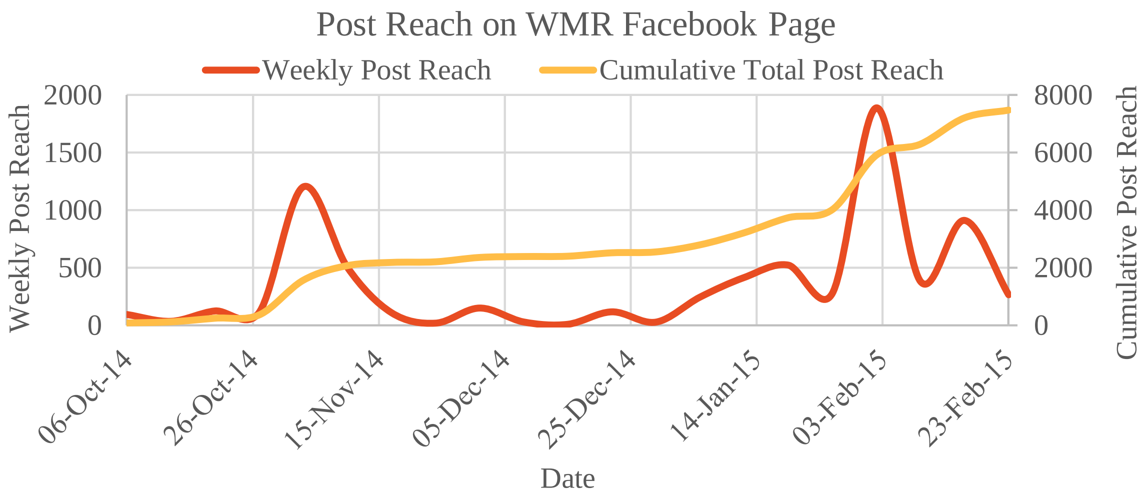


Figure 13: WMR Facebook Post Reach

5.3 Outreach

WMR has focussed on using both the existing WMR robots and Orion as an educational platform. The team have attended several events including Imagineering 2014, the 3D Printing in Schools Showcase at the Herbert Art Gallery (shown in Figure 14 and 15 respectively) and several recruitment events at WMG and the University of Warwick in pursuit of encouraging the next generation into both robotics and STEM subjects. The team will also be attending the Cheltenham Science Festival in June.

Figure 14: WMR at Imagineering 2014

Figure 15: WMR at the 3D Printing in Schools Showcase at the Herbert Art Gallery

6 Discussion

WMR aimed to design and build a robust and durable robot platform suitable for further development. The drivetrain design was crucial to achieving such characteristics and was consequently the most capital-intensive design feature, accounting for 62.8% of the material costs, as shown in Table 1. The total material and manufacturing costs incurred summated to £4082.94. As the aim of this project was to provide a platform for future development, this expenditure can be considered as an investment for further research. Significant savings on components were achieved through sponsorship, saving WMR approximately £520 on materials.

The total manufacturing cost, including tooling and outsourcing to specialist manufacturers, represents 17.6% of the total material costs. This was the only over-budget aspect of the project. However, with other aspects under budget, seeking additional manufacturing assistance was financially viable. At project end, WMR had a total surplus of £1156.82.

Throughout the duration of the project the WMR team have generated both a detailed long-term project plan and a handover guide for the 2015/16 team. This handbook has been produced in the aim of reducing the initial complexity of the project, providing justification for the current designs and areas of recommended improvement. This will add significant value to the project next year through the saving of time and hence labour costs.

The total project cost was £59,466.94, comprising of labour, materials and manufacturing costs. The key benefit of this project is the contribution to a research field that has the potential to save many human lives. A human life is currently valued at £6.1m (Partnoy, 2012) so the total project cost can be justified as a small investment leading to significant potential savings.

7 Conclusion

The key benefits of this project include a significant contribution to USAR research for saving lives, knowledge and experience gained by students, academics and the wider society, inspiration of younger generations to study engineering and STEM subjects through outreach events and enhanced supplier relationships obtained for future WMR teams and the University. The total project cost is £59,466.94, comprising of labour, materials and manufacturing costs. When compared to the cost of an individual human life, the costs incurred over the duration of this project can be justified as a small contribution to a research field leading to significant potential savings.

8 References

Fryer, T., 2015. *Robots to the Rescue*. [Online]
Available at: http://www.eurekamagazine.co.uk/design-engineering-news/robots-to-the-rescue/72836/ http://www.maxonmotor.co.uk/maxon/view/news/Newminiaturerescuerobot
[Accessed 21 April 2015].

Hokuyo Automatic, 2009. *Hokuyo URG-04LX*. [Online]
Available at: https://www.hokuyo-aut.jp/02sensor/07scanner/urg_04lx.html
[Accessed 17 04 2015].

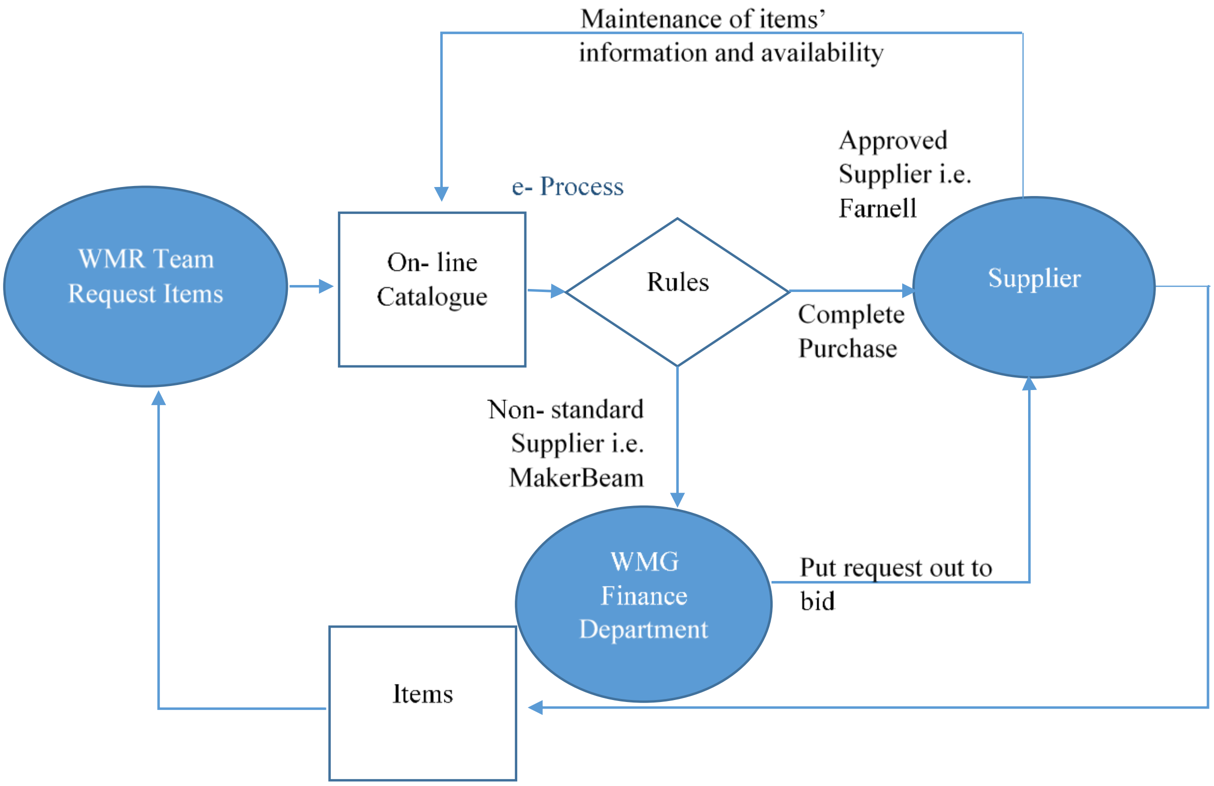
Maxon Motor, 2015. *Getting to Know: Rebecca Saunders, Warwick Mobile Robotics.* [Online]
Available at:
http://www.maxonmotor.co.uk/maxon/view/news/GettingtoKnowRebeccaSaundersWarwickMobileRobotics
[Accessed 21 April 2015].

Partnoy, F., 2012. *The Cost of a Human Life, Statistically Speaking.* [Online]
Available at: http://www.theglobalist.com/the-cost-of-a-human-life-statistically-speaking/
[Accessed 21 April 2015].

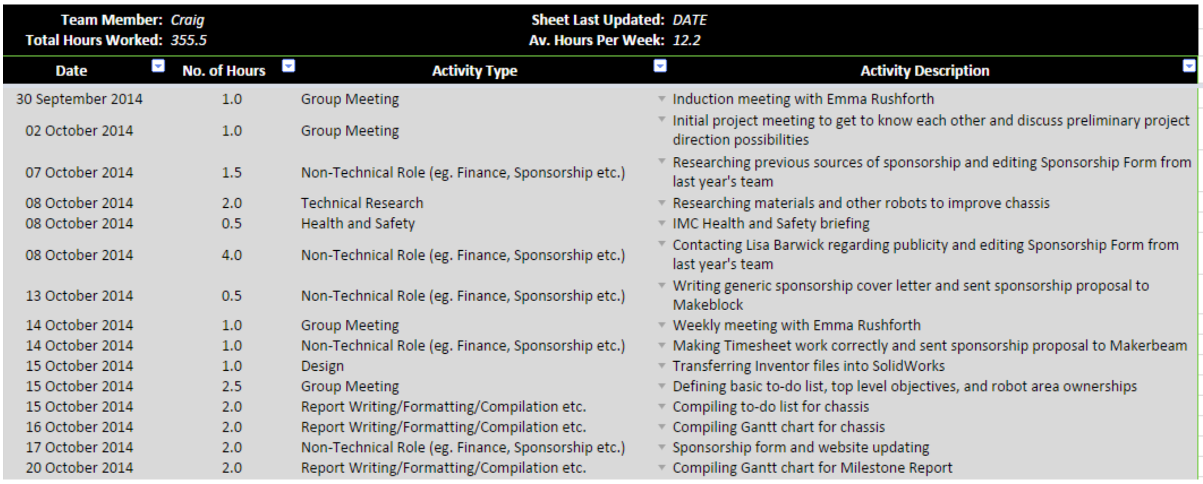
Appendices

Appendix A: OPERA Purchasing System

OPERA, the university's e-purchasing system, was used for the procurement of supplies and equipment for the USAR robot. As shown below, this process covered purchasing from approved and non- standard suppliers, receiving, paying for and accounting of goods and services. This system enabled visibility into the numerous purchases; quick identification of suppliers and overall reduction in manpower costs and purchase orders. However, this system didn't include the physical distribution of these items and processing returns.



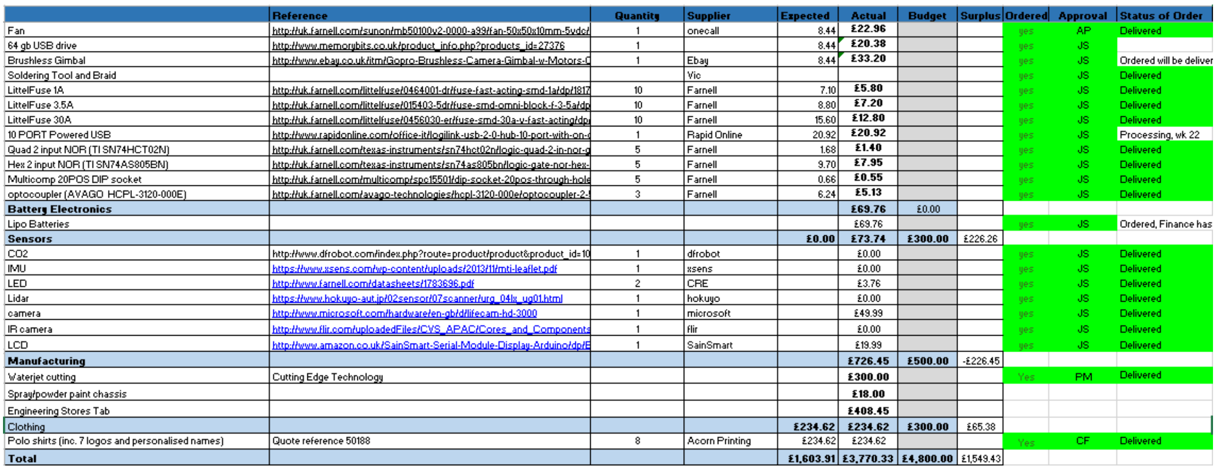
Appendix B: Example Timesheet



Team Member: *Craig* **Sheet Last Updated:** *DATE*
Total Hours Worked: *355.5* **Av. Hours Per Week:** *12.2*

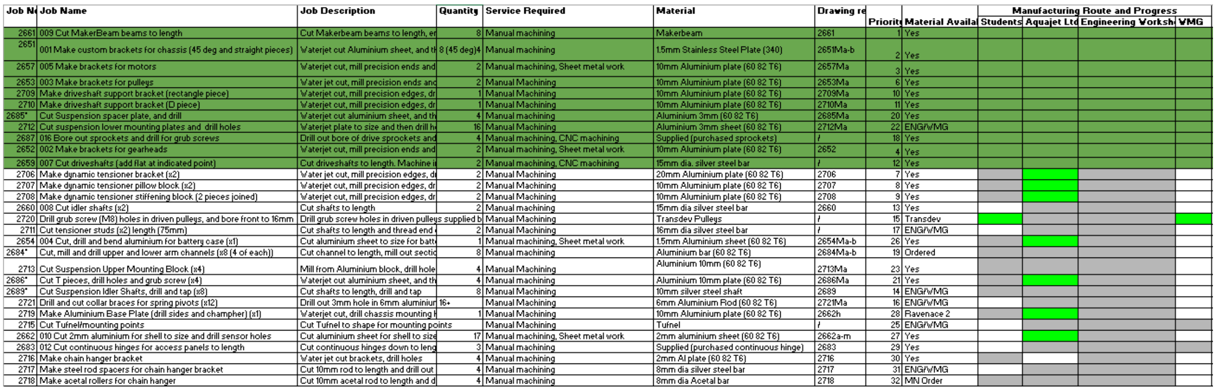
Date	No. of Hours	Activity Type	Activity Description
30 September 2014	1.0	Group Meeting	Induction meeting with Emma Rushforth
02 October 2014	1.0	Group Meeting	Initial project meeting to get to know each other and discuss preliminary project direction possibilities
07 October 2014	1.5	Non-Technical Role (eg. Finance, Sponsorship etc.)	Researching previous sources of sponsorship and editing Sponsorship Form from last year's team
08 October 2014	2.0	Technical Research	Researching materials and other robots to improve chassis
08 October 2014	0.5	Health and Safety	IMC Health and Safety briefing
08 October 2014	4.0	Non-Technical Role (eg. Finance, Sponsorship etc.)	Contacting Lisa Barwick regarding publicity and editing Sponsorship Form from last year's team
13 October 2014	0.5	Non-Technical Role (eg. Finance, Sponsorship etc.)	Writing generic sponsorship cover letter and sent sponsorship proposal to Makeblock
14 October 2014	1.0	Group Meeting	Weekly meeting with Emma Rushforth
14 October 2014	1.0	Non-Technical Role (eg. Finance, Sponsorship etc.)	Making Timesheet work correctly and sent sponsorship proposal to Makerbeam
15 October 2014	1.0	Design	Transferring Inventor files into SolidWorks
15 October 2014	2.5	Group Meeting	Defining basic to-do list, top level objectives, and robot area ownerships
15 October 2014	2.0	Report Writing/Formatting/Compilation etc.	Compiling to-do list for chassis
16 October 2014	2.0	Report Writing/Formatting/Compilation etc.	Compiling Gantt chart for chassis
17 October 2014	2.0	Non-Technical Role (eg. Finance, Sponsorship etc.)	Sponsorship form and website updating
20 October 2014	2.0	Report Writing/Formatting/Compilation etc.	Compiling Gantt chart for Milestone Report

Appendix C: Budget & Tech List



	Reference	Quantity	Supplier	Expected	Actual	Budget	Surplus	Ordered	Approval	Status of Order
Fan	http://uk.farnell.com/sunon/mb50100v2-0000-a99/fan-50x50x10mm-5vdc/	1	onecall	8.44	**£22.96**			yes	AP	Delivered
64 gb USB drive	http://www.memorybits.co.uk/product_info.php?products_id=27376	1		8.44	**£20.38**			yes	JS	
Brushless Gimbal	http://www.ebay.co.uk/itm/Gopro-Brushless-Camera-Gimbal-w-Motors-C	1	Ebay	8.44	**£33.20**			yes	JS	Ordered will be deliver
Soldering Tool and Braid			Vic					yes	JS	Delivered
LittelFuse 1A	http://uk.farnell.com/littelfuse/0464001-dr/fuse-fast-acting-smd-1a/dp/1817	10	Farnell	7.10	**£5.80**			yes	JS	Delivered
LittelFuse 3.5A	http://uk.farnell.com/littelfuse/015403-5dr/fuse-smd-omni-block-f-3-5a/dp	10	Farnell	8.80	**£7.20**			yes	JS	Delivered
LittelFuse 30A	http://uk.farnell.com/littelfuse/0456030-er/fuse-smd-30a-v-fast-acting/dp	10	Farnell	15.60	**£12.80**			yes	JS	Delivered
10 PORT Powered USB	http://www.rapidonline.com/office-it/logilink-usb-2-0-hub-10-port-with-on-	1	Rapid Online	20.92	**£20.92**			yes	JS	Processing, wk 22
Quad 2 input NOR (TI SN74HCT02N)	http://uk.farnell.com/texas-instruments/sn74hct02n/logic-quad-2-in-nor-g	5	Farnell	1.68	**£1.40**			yes	JS	Delivered
Hex 2 input NOR (TI SN74AS805BN)	http://uk.farnell.com/texas-instruments/sn74as805bn/logic-gate-nor-hex-	5	Farnell	9.70	**£7.95**			yes	JS	Delivered
Multicomp 20POS DIP socket	http://uk.farnell.com/multicomp/spc15501/dip-socket-20pos-through-hole	5	Farnell	0.66	**£0.55**			yes	JS	Delivered
optocoupler (AVAGO HCPL-3120-000E)	http://uk.farnell.com/avago-technologies/hcpl-3120-000e/optocoupler-2-	3	Farnell	6.24	**£5.13**			yes	JS	Delivered
Battery Electronics					**£69.76**	£0.00				
Lipo Batteries					£69.76			yes	JS	Ordered, Finance has
Sensors				**£0.00**	**£73.74**	**£300.00**	£226.26			
CO2	http://www.dfrobot.com/index.php?route=product/product&product_id=10	1	dfrobot		£0.00			yes	JS	Delivered
IMU	https://www.xsens.com/wp-content/uploads/2013/11/mti-leaflet.pdf	1	xsens		£0.00			yes	JS	Delivered
LED	http://www.farnell.com/datasheets/1783696.pdf	2	CRE		£3.76			yes	JS	Delivered
Lidar	https://www.hokuyo-aut.jp/02sensor/07scanner/urg_04lx_ug01.html	1	hokuyo		£0.00			yes	JS	Delivered
camera	http://www.microsoft.com/hardware/en-gb/d/lifecam-hd-3000	1	microsoft		£49.99			yes	JS	Delivered
IR camera	http://www.flir.com/uploadedFiles/CVS_APAC/Cores_and_Components	1	flir		£0.00			yes	JS	Delivered
LCD	http://www.amazon.co.uk/SainSmart-Serial-Module-Display-Arduino/dp/B	1	SainSmart		£19.99			yes	JS	Delivered
Manufacturing					**£726.45**	**£500.00**	-£226.45			
Waterjet cutting	Cutting Edge Technology				**£300.00**			Yes	PM	Delivered
Spray/powder paint chassis					**£18.00**					
Engineering Stores Tab					**£408.45**					
Clothing				**£234.62**	**£234.62**	**£300.00**	£65.38			
Polo shirts (inc. 7 logos and personalised names)	Quote reference 50188	8	Acorn Printing	£234.62	£234.62			Yes	CF	Delivered
Total				**£1,603.91**	**£3,770.33**	**£4,800.00**	£1,549.43			

Appendix D: Manufacturing Priority List



Job N	Job Name	Job Description	Quantity	Service Required	Material	Drawing re			Manufacturing Route and Progress			
							Priority	Material Availal	Students	Aquajet Ltd	Engineering Worksh	VMG
2661	009 Cut MakerBeam beams to length	Cut Makerbeam beams to length, en	8	Manual machining	Makerbeam	2661	1	Yes				
2651	001 Make custom brackets for chassis (45 deg and straight pieces)	Waterjet cut Aluminium sheet, and th	8 (45 deg)4	Manual machining	1.5mm Stainless Steel Plate (340)	2651Ma-b	2	Yes				
2657	005 Make brackets for motors	Waterjet cut, mill precision ends and	2	Manual machining, Sheet metal work	10mm Aluminium plate (60 82 T6)	2657Ma	3	Yes				
2653	003 Make brackets for pulleys	Water jet cut, mill precision ends and	2	Manual Machining	10mm Aluminium plate (60 82 T6)	2653Ma	6	Yes				
2709	Make driveshaft support bracket (rectangle piece)	Waterjet cut, mill precision edges, dr	1	Manual Machining	10mm Aluminium plate (60 82 T6)	2709Ma	10	Yes				
2710	Make driveshaft support bracket (D piece)	Waterjet cut, mill precision edges, dr	1	Manual Machining	10mm Aluminium plate (60 82 T6)	2710Ma	11	Yes				
2685*	Cut Suspension spacer plate, and drill	Waterjet cut aluminium sheet, and th	4	Manual machining	Aluminium 3mm (60 82 T6)	2685Ma	20	Yes				
2712	Cut suspension lower mounting plates and drill holes	Waterjet plate to size and then drill h	16	Manual Machining	Aluminium 3mm sheet (60 82 T6)	2712Ma	22	ENG/WMG				
2687	016 Bore out sprockets and drill for grub screws	Drill out bore of drive sprockets and	4	Manual machining, CNC machining	Supplied (purchased sprockets)	/	18	Yes				
2652	002 Make brackets for gearheads	Waterjet cut, mill precision ends and	2	Manual machining, Sheet metal work	10mm Aluminium plate (60 82 T6)	2652	4	Yes				
2659	007 Cut driveshafts (add flat at indicated point)	Cut driveshafts to length. Machine i	2	Manual machining, CNC machining	15mm dia. silver steel bar	/	12	Yes				
2706	Make dynamic tensioner bracket (x2)	Water jet cut, mill precision edges, dr	2	Manual Machining	20mm Aluminium plate (60 82 T6)	2706	7	Yes	▨	🟩	▨	
2707	Make dynamic tensioner pillow block (x2)	Waterjet cut, mill precision edges, dr	2	Manual Machining	10mm Aluminium plate (60 82 T6)	2707	8	Yes	▨	🟩	▨	
2708	Make dynamic tensioner stiffening block (2 pieces joined)	Waterjet cut, mill precision edges, dr	2	Manual Machining	10mm Aluminium plate (60 82 T6)	2708	9	Yes	▨	🟩	▨	
2660	008 Cut idler shafts (x2)	Cut shafts to length	2	Manual machining	15mm dia silver steel bar	2660	13	Yes		▨	▨	
2720	Drill grub screw (M8) holes in driven pulleys, and bore front to 16mm	Drill grub screw holes in driven pulleys supplied b		Manual Machining	Transdev Pulleys	/	15	Transdev	🟩	▨	▨	🟩
2711	Cut tensioner studs (x2) length (75mm)	Cut shafts to length and thread end	2	Manual Machining	16mm dia silver steel bar	/	17	ENG/WMG		▨	▨	
2654	004 Cut, drill and bend aluminium for battery case (x1)	Cut aluminium sheet to size for batt	1	Manual machining, Sheet metal work	1.5mm Aluminium sheet (60 82 T6)	2654Ma-b	26	Yes	▨	🟩	▨	
2684*	Cut, mill and drill upper and lower arm channels (x8 (4 of each))	Cut channel to length, mill out sectio	8	Manual machining	Aluminium bar (60 82 T6)	2684Ma-b	19	Ordered	▨	▨	▨	
2713	Cut Suspension Upper Mounting Block (x4)	Mill from Aluminium block, drill hole	4	Manual Machining	Aluminium 10mm (60 82 T6)	2713Ma	23	Yes	▨	▨	▨	
2686*	Cut T pieces, drill holes and grub screw (x4)	Waterjet cut aluminium sheet, and th	4	Manual machining	Aluminium 10mm plate (60 82 T6)	2686Ma	21	Yes	▨	🟩	▨	
2689*	Cut Suspension Idler Shafts, drill and tap (x8)	Cut shafts to length, drill and tap	8	Manual Machining	10mm silver steel shaft	2689	14	ENG/WMG	▨	▨	▨	
2721	Drill and cut collar braces for spring pivots (x12)	Drill out 3mm hole in 6mm aluminiur	16+	Manual Machining	6mm Aluminium Rod (60 82 T6)	2721Ma	16	ENG/WMG		▨	▨	
2719	Make Aluminium Base Plate (drill sides and champher) (x1)	Waterjet cut, drill chassis mounting h	1	Manual Machining	10mm Aluminium plate (60 82 T6)	2662h	28	Ravenace 2	▨	🟩	▨	
2715	Cut Tufnel/mounting points	Cut Tufnel to shape for mounting points		Manual Machining	Tufnel	/	25	ENG/WMG		▨	▨	▨
2662	010 Cut 2mm aluminium for shell to size and drill sensor holes	Cut aluminium sheet for shell to size	17	Manual machining, Sheet metal work	2mm aluminium sheet (60 82 T6)	2662a-m	27	Yes		🟩	▨	
2683	012 Cut continuous hinges for access panels to length	Cut continuous hinges down to leng	3	Manual machining	Supplied (purchased continuous hinge)	2683	29	Yes		▨	▨	▨
2716	Make chain hanger bracket	Water jet cut brackets, drill holes	4	Manual machining	2mm Al plate (60 82 T6)	2716	30	Yes	▨		▨	
2717	Make steel rod spacers for chain hanger bracket	Cut 10mm rod to length and drill out	4	Manual machining	8mm dia silver steel bar	2717	31	ENG/WMG		▨	▨	
2718	Make acetal rollers for chain hanger	Cut 10mm acetal rod to length and d	4	Manual machining	8mm dia Acetal bar	2718	32	MN Order	▨	▨	▨	

Appendix E: Why is our CBA different?

As demonstrated, Cost-Benefit Analysis (CBA) is a common approach to project evaluation in regards to the costs incurred and its associated benefits. However, Arrow[1] explicitly discussed various analysts use CBA to measure a project's contribution to welfare, while others use it solely for the project's efficiency. As the centre focus of these two are conflicting, an actual definition of CBA is appropriate. In Nyborg's findings[2], the author expressed pinpointing what CBA actually measures is remarkably hard. The reason is as such: normally, economic textbooks assume the aim of CBA is to evaluate a project's social welfare in respect to a known policy-making entity such as the government.

Our CBA's starting point is *somewhat* different. This CBA's main assumption is that individual participants in this project such as students and academics critique social effects from their own perspectives. This is fundamental as the ethical and political views of all these participants are likely to vary.

From this, CBA's definition in this context could be society's net willingness to pay for the Urban Search and Rescue Robot. Moreover, in terms of environmental factors, does conducting CBA prevent these issues being disregarded? In hindsight, there is no definite answer to that question. Also, in this project, how does one quantify in monetary terms the environmental turbulence that an Urban Search and Rescue Robot will travel through? WMR used EC-4 Pole 22 Maxon Motors to power the robot. It leads one to inquire the motors' impact on the environment.