UNIVERSITY OF WARWICK
SCHOOL OF ENGINEERING

Warwick Mobile Robotics: Urban Search and Rescue Robot

ES410 Group Project Cost Benefit Analysis Report

02/05/13

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WORD COUNT: 1498

1 Introduction

This Cost Benefit Analysis assesses the merits realised by the Warwick Mobile Robotics (WMR) project and provides justification for the time and costs incurred. WMR have developed their Urban Search and Rescue Robot (USARR); a machine intended to assist professional response teams with the recovery of victims in disaster zones by navigating areas deemed unsafe for humans.

2 Objectives

The 2012/2013 aims:

- Participate in the World Robocup Rescue competition 2013
- Make the USARR more viable for real world applications

A SWOT analysis (Appendix A) highlighted three areas for improvement with objectives to achieve these:

1. Improve reliability:
   Unreliability, with functions failing on start-up, has been detrimental in past competitions. An unreliable system cannot be used in real-world disaster scenarios where lives are at risk.

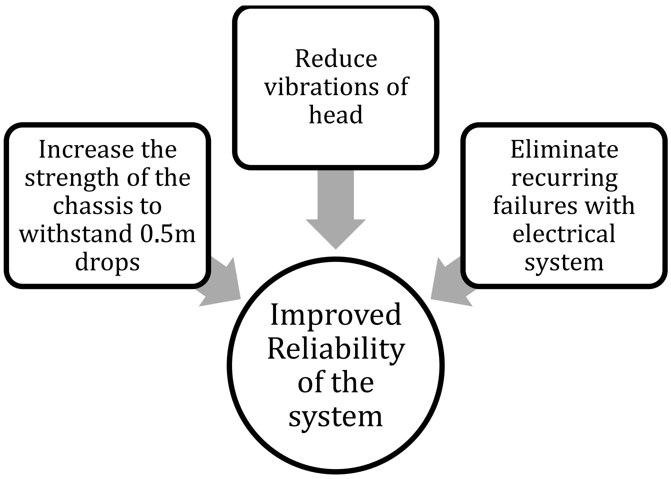

Figure 1. Objectives to improve reliability

2. Improve operator control and awareness:
Operator control is commercially important: intuitive control requires less training, resulting in quicker task execution with higher precision. Operator awareness allows more confident assessment of remote situations.

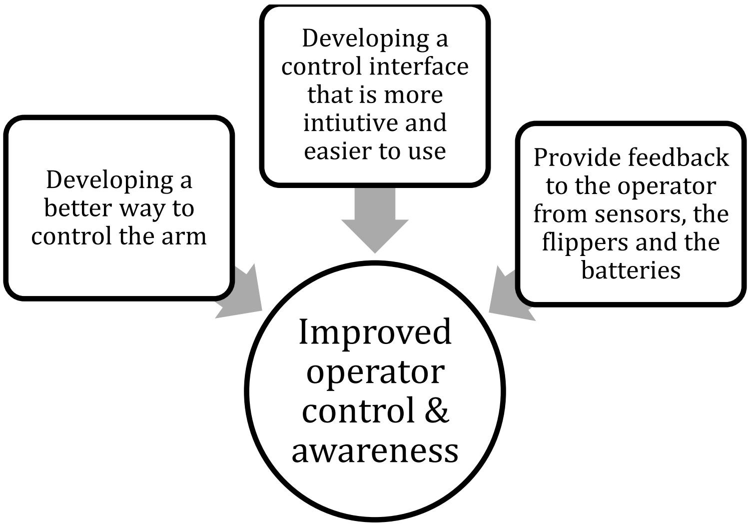

Figure 2. Objectives to improve operator control

3. Progress towards real world readiness:
In realistic situations, the robot must perform in unfavourable conditions. Testing can highlight areas for improvement and ensure the final design would meet a buyer's requirements.

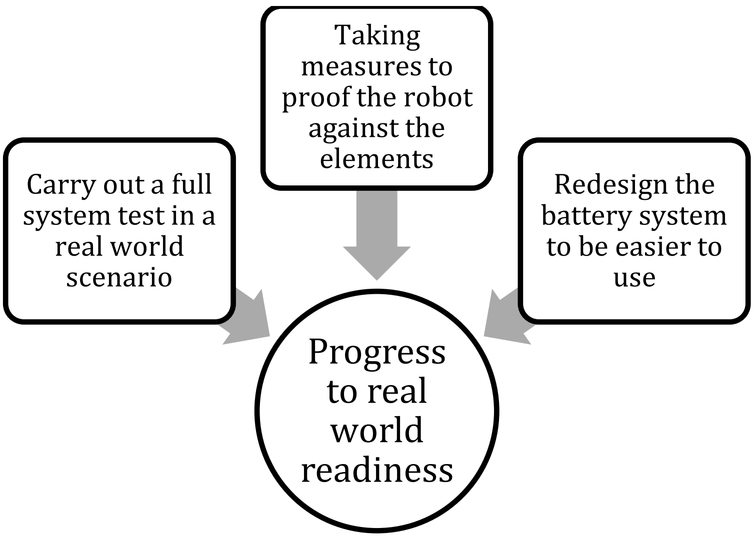

Figure 3. Objectives to progress real world readiness.

Reassessment and reassigning of objectives resulted from the unanticipated loss of a team member. All objectives were met by tasks being allocated to individuals (Appendix B); these were logged and updated using a Gantt chart.

3 What work was undertaken, why and how?

3.1 Space Frame

The new space frame is lighter and more robust (Figure 4) - the previous chassis had endured flipper bracket bending and excessive vibrations. Designs were tested physically (Inertial Measurement Unit attached to the flippers and driven from a 0.35m height (Figure 5)) and virtually (SolidWorks).

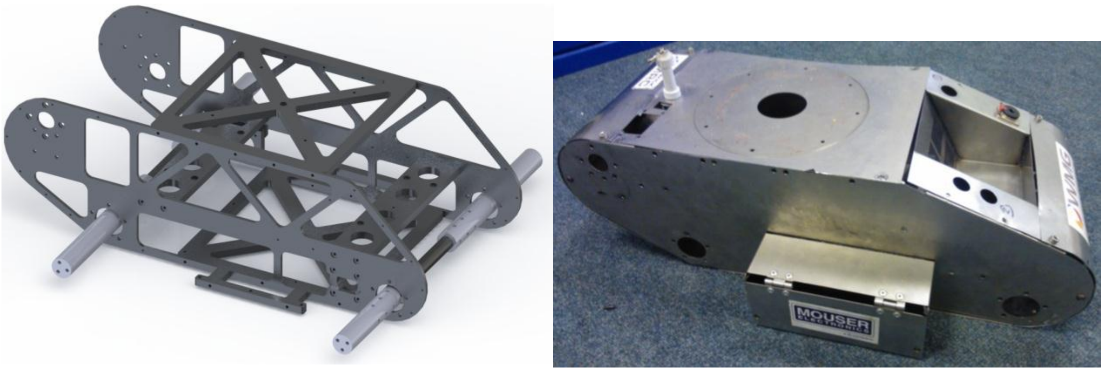

Figure 4. Left: New Frame, Right: Old Chassis

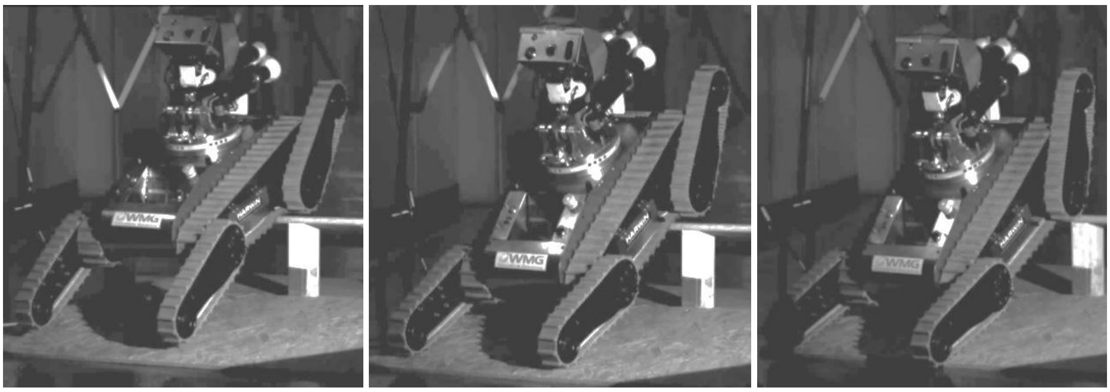

Figure 5. Time-lapse of high-speed footage

3.2 Shell

A new shell has been manufactured (Figure 6) using ABS to protect inner components and also increase accessibility for maintenance through a removable lid.

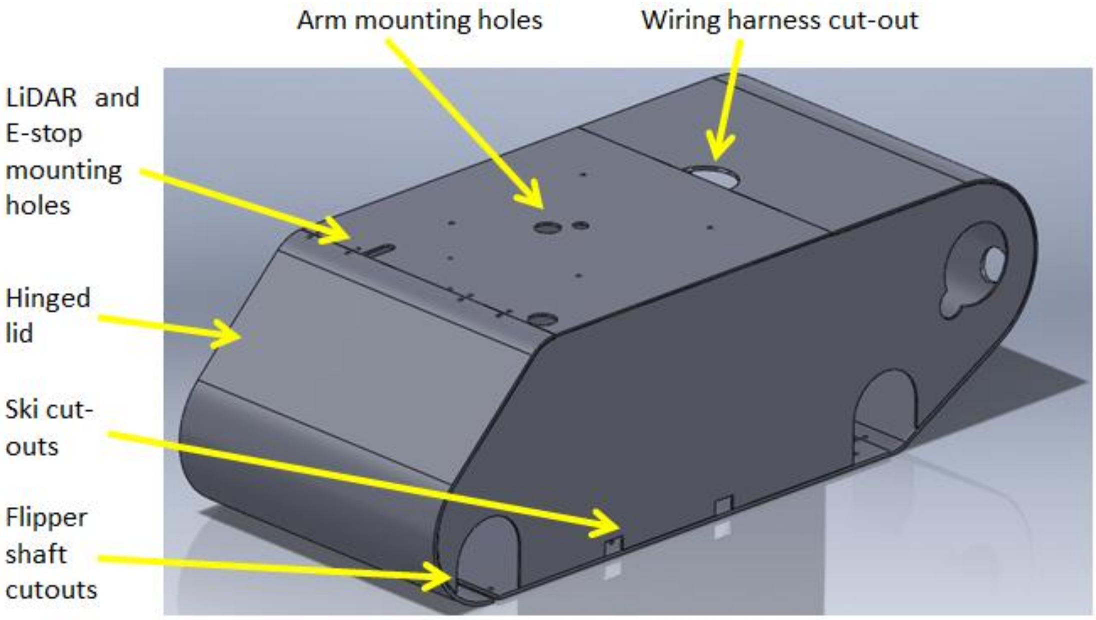

Figure 6. New Shell Design on SolidWorks

3.3 Power Board

A more compact power distribution board uses high-reliability (Harwin plc, 2013) connectors because the old power distribution board was unreliable and too large for the new chassis (Figure 7). 50W DC/DC converters with heat-sinks improve reliability / operating temperature range and small footprint power-FETs reduce board size.

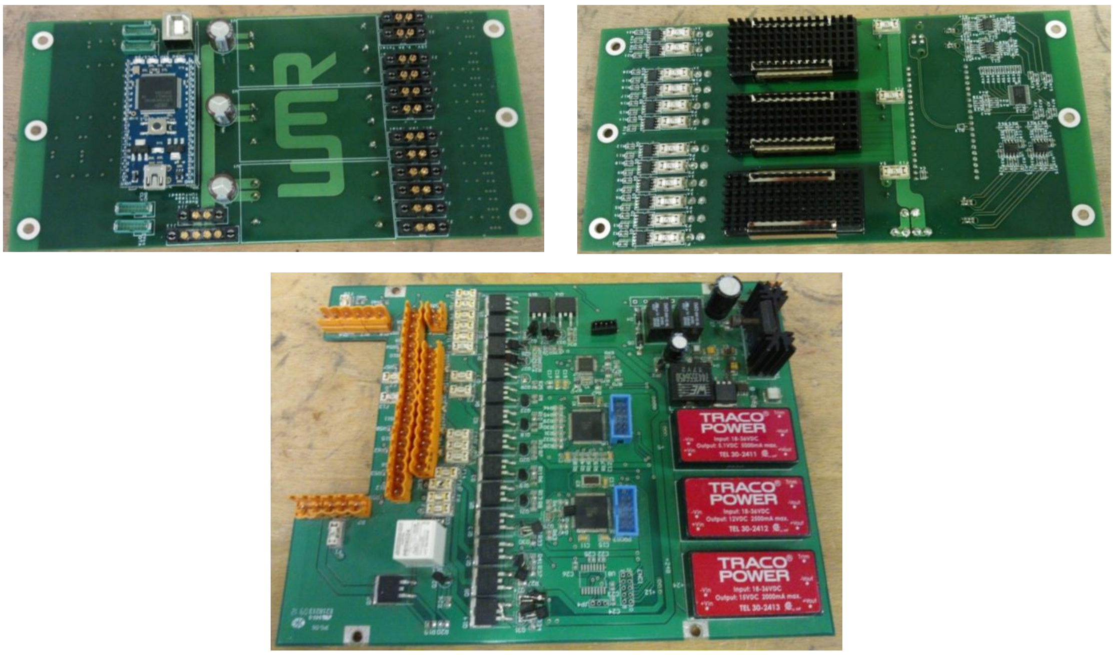

Figure 7. Top: New power board design. Bottom: Old design

3.4 Battery Monitoring

A new battery management circuit protects against over/undervoltage, short-circuits and excessive discharge currents, with a fuel-gauge monitoring battery charge (Figure 8). Previously only an external alarm unit warned of a cell's undervoltage. The new design uses two ICs – one for protection, one for fuel-gauging.

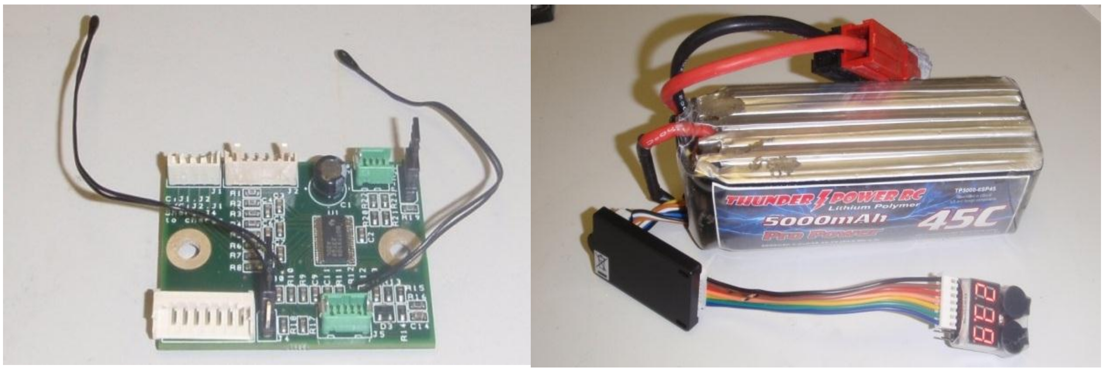

Figure 8. Left: New battery monitoring circuit, Right: Old system

3.5 Battery Enclosure

Batteries are now located higher up inside the front of the robot, allowing for safe traversing of rubble, with a new battery pack allowing easy insertion/removal. FEA on the ABS housing indicated 3mm optimal thicknesses. Guiding rails on the 3D printed part ensure accurate connector alignment.

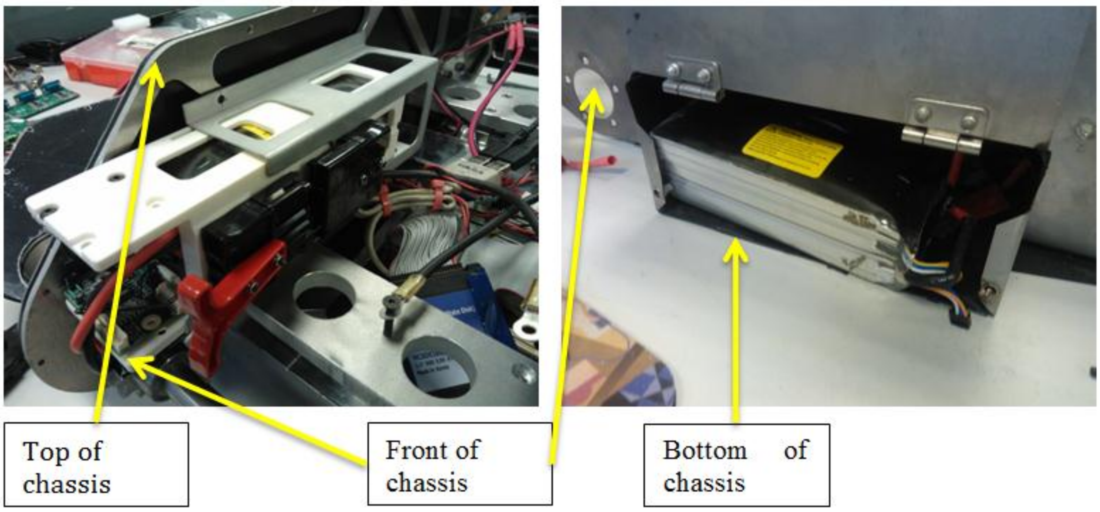

Figure 9. Above: New battery enclosure, Below: Previous battery enclosure

3.6 Sensors

The CO_2 sensor, gripper, LiDAR, webcams, IMU and infrared camera are now functioning (they were not before). The previously haphazard wiring has been systematically redone and a microcontroller now collects CO_2 sensor data and provides PWM (Pulse Width Modulation) for the gripper.

3.7 Head Redesign

A new head includes a removable lid to optimise maintenance access (Figure 10). ABS plastic (high impact resistance) was used to lightweight by 29% and to reduce vibrations. 3D printing was used customize compartments to fit each component. The removable sliding lid is less susceptible to dust and rain.

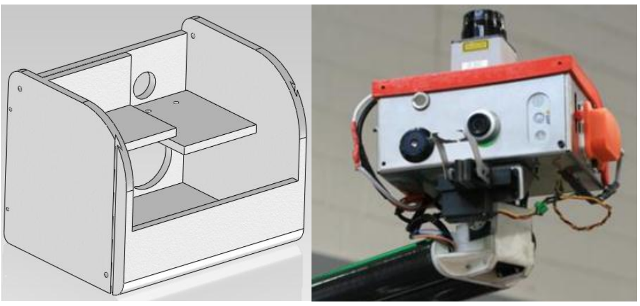

Figure 10. Left: New head design, Right: Previous head design

3.8 Inverse Kinematics

Inverse kinematics was implemented to make using the arm more intuitive. The two planes of motion (cylindrical and Cartesian co-ordinate frame) were modelled separately and the equations combined (Figure 11).

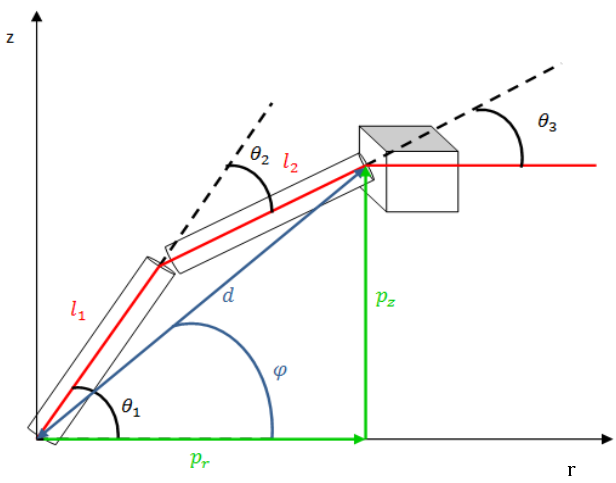

Figure 11. Arm in the Cartesian coordinate frame

3.9 GUI (Graphical User Interface)

3D representation has been included within an improved GUI to enhance driver awareness of surroundings.

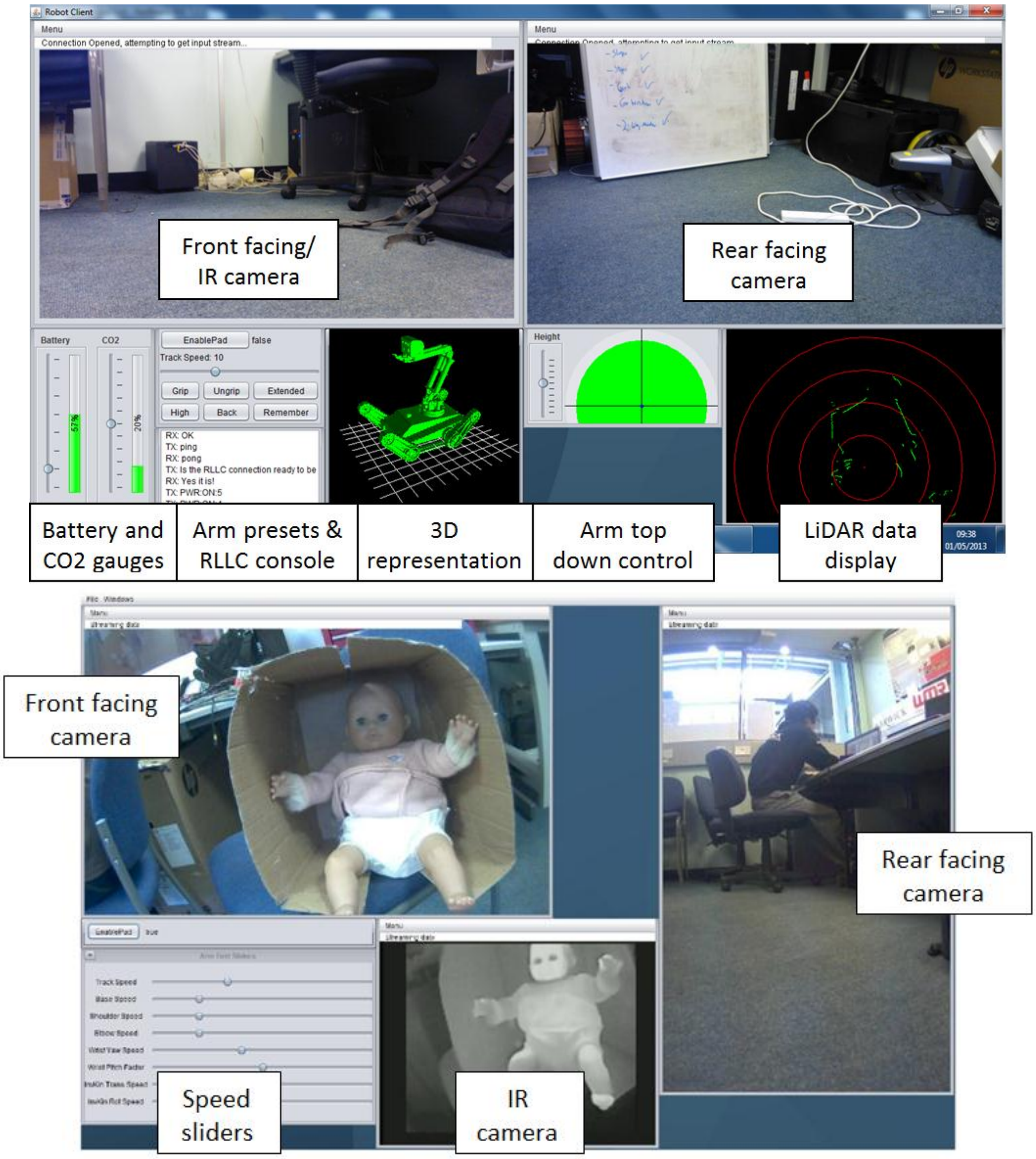

Figure 12. Above: New GUI design, Below: Old GUI design

3.10 Testing

Partnership with Remotec (Northrop Grumman, 2013) allowed WMR to conduct structured outdoors testing at an industry facility for the first time ever. This was used to assess how well the team has achieved its aims and objectives.

Figure 13. Mobile operator performing testing

4 Cost Benefit Analysis

4.1 Full Costing

Project total cost was £54,821.59, comprising of material (competition travel included) and labour costs (hourly wage includes overheads).

4.1.1 Material Costs

Material cost total was £8,765.59. Table 1 shows a breakdown of costs (full details in Appendix C).

Table 1. Material costs by category

Component	Material Costs
Chassis	£1,265.98
Power System	£2,179.32
Sensors and Devices	£618.82
Miscellaneous	£201.47
Travel Budget	£4,500.00
TOTAL	**£8,765.59**

4.1.2 Labour Costs

WMR have performed the majority of labour, technicians have completed manufacturing tasks and academic directors provided advice and support (Table 2).

Table 2. Hours worked by person from Gantt chart

Position	Person	Hours	Cost (£)
Student (£15/hour)	Kristian Buckstone	498	7470
	Lewis Judd	388	5820
	Nicholas Orlowski	323	4845
	Michael Tayler-Grint	424	6360
	Matthew Truscott[1]	84	1260
	Rachele Williams	357	5355
	Edgars Zauls	519	7785
Technician (£30/hour)	Carl Lobjoit	125	3750
Project Director (£75/hour)	Dr Peter Jones	18	1350
	Dr Emma Rushforth	23	1725
Other academic (£50/hour)	Stefan Winkvist – PhD student	35	1750
	Jeffrey Youngblood – Associate Professor of Materials Engineering	1	50
		Total labour costs:	**47520**

The Gantt chart associated with labour costs (Appendix D) is summarised in the Figure 14 flow diagram.

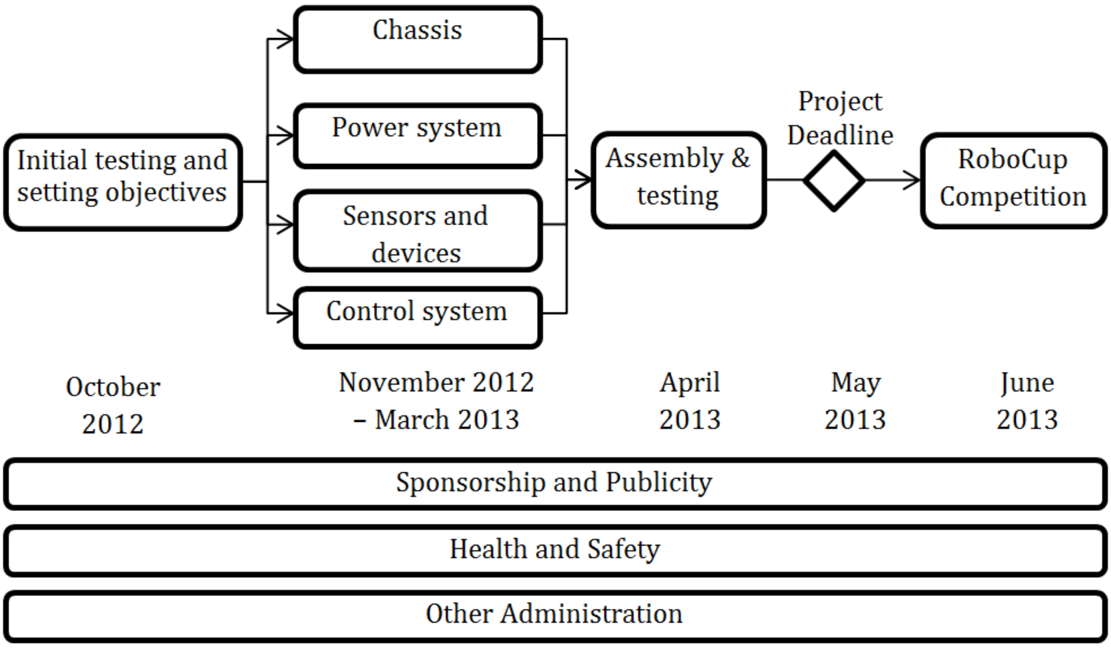

Figure 14. Summarised Project timeline.

Table 3 depicts allotment of labour to tasks.

Table 3. Total hours worked by task.

Task	Pay grade	Hours worked	Cost (£)
Chassis	Student (£15/hour)	475	7132
	Technician (£30/hour)	125	3750
Power System	Student (£15/hour)	216	3247
Sensors and Devices	Student (£15/hour)	207	3105
Control System	Student (£15/hour)	200	3000
Assembly & Testing	Student (£15/hour)	192	2880
Reports	Student (£15/hour)	694	10410
Sponsorship & Publicity	Student (£15/hour)	310	4657
Competition	Student (£15/hour)	84	1260
Other	Student (£15/hour)	236	3540
	Project Director (£75/hour)	41	3075
Total labour costs:			**46056**

4.1.3 Total Costs

The total costs for WMR this year are shown in Table 4.

Table 4. Total costs

Category	Cost	Portion of Total Cost
Chassis	£12,147.98	22%
Power System	£5,426.32	10%
Sensors & Devices	£3,723.82	7%
Control System	£3,000.00	5%
Assembly & Testing	£2,880.00	5%
Reports	£10,410.00	19%
Sponsorship & Publicity	£4,657.00	9%
Competition	£5,760.00	11%

Figure 15 visually depicts the breakdown of total costs.

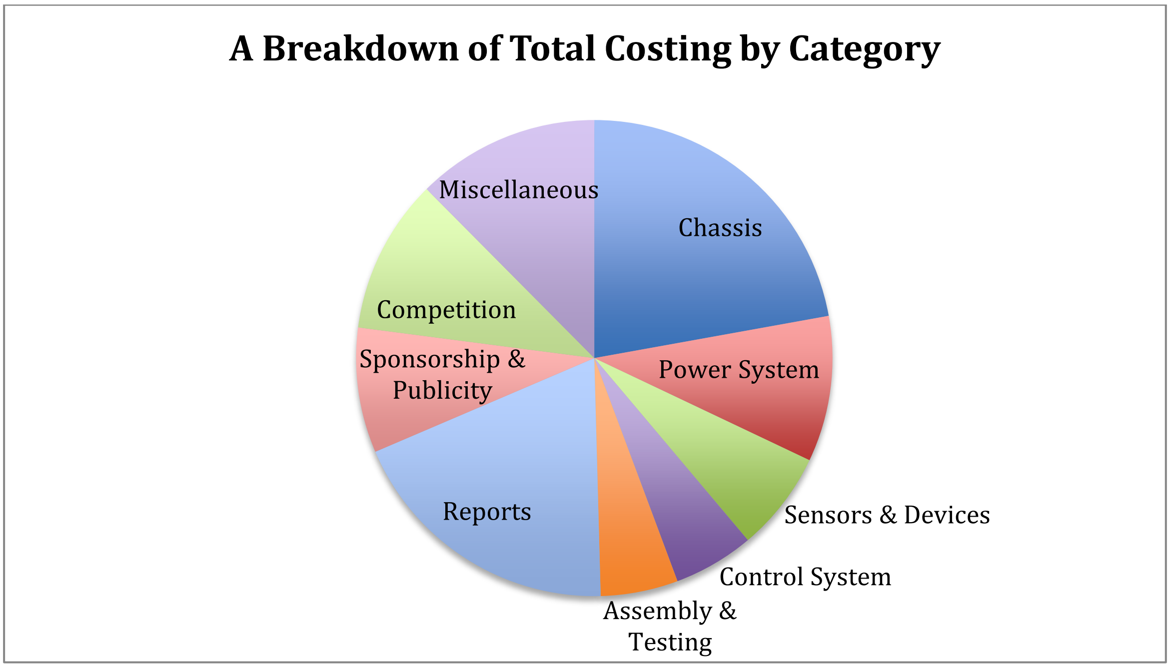

Figure 15. Total costs by category.

4.1.4 Re-manufacture Costs

For commercial release, the cost for complete re-manufacture (materials only) is £10,937.84

(Appendix E).

4.2 Benefits

4.2.1 Benefits to students

- Development of skills in Robotic engineering and specific degree disciplines can be applied to PhD research or specialist engineering jobs
- Development of time management, finance organisation and task allocation abilities
- Collaboration between degree disciplines has improved sub-system integration
- Commercial experience from working with an organisation's administrative procedures and external sponsor organisations
- Improved reliability will allow WMR 2013/2014 to develop functionality without start-up delays, using lessons passed on from the World competition.

4.2.2 Benefits to academics

- Technology applied to renowned disasters will endorse engineering, robotics technology and Warwick University, especially through continued publicity
- Relationships with industry and sponsors can be maintained and developed
- New research themes can be identified and funded using past achievements
- Development of Robotics related teaching material
- Advancement in robotics knowledge to assist future disaster response solutions
- Expertise can be applied to commercial challenges, e.g. establishing a centre of expertise with Catapult to rival UK and International institutions.

4.2.3 Benefits to wider society

- Deployment of an USARR could reduce risks to professional disaster response teams, preventing further casualties. (Burke, 2003)
- This year's design has progressed towards being able to be used in a disaster situation; in particular:
  - Improved reliability, crucial for fast-paced emergency scenario
  - Strengthened chassis allows for operation in more demanding environments

- A more intuitive control system is valuable where operators may have minimal training
- More "off the shelf" parts for cheaper and easy re-build (Bishop, Crabbe, & Hudock, 2012). Cost reduction permits use of multiple robot teams to search greater areas, or back-up machines.

4.3 Outcomes and Achievements

4.3.1 Learning outcomes

Alongside technical and management learning outcomes mentioned in section 5.2.1, the following lessons have been developed:

1. Dealing with unpredictability. Suppliers add uncertainty, so the team has learned to create back up plans to mitigate risks that could disrupt the project.
2. Coping with long lead times. Manufacturing processes can be lengthy and the team has learned to multi-task and reassess tasks whilst waiting on completion of jobs.

4.3.2 Sponsorship and Publicity

As well as maintaining relationships with existing sponsors WMG (WMG, 2013), Harwin, Mouser Electronics (Mouser Electronics, 2013), Maxon Motor (Maxon motor ag, 2013), School of Engineering (Warwick School of Engineering, 2013) and the Vice Chancellor (Thrift), WMR has acquired three new sponsorship partners.

CATAPULT High Value Manufacturing

WMG centre HVM Catapult has provided monetary assistance for lightweight materials, energy storage and management.

The Institution of Mechanical Engineers (Institution of Mechanical Engineers, 2013) has provided a Group project award to support travel to the World Robocup competition.

Remotec, part of Northrop Grumman Corporation (Northrop Grumman, 2013), have formed a partnership with WMR to share technical expertise and provide testing facilities.

Publicity activities have promoted WMR and engineering at Warwick University, such as attending the Coventry Imagineering Fair (The Imagineering Foundation, 2012) and articles published as local press releases and in professional engineering magazines.

4.3.3 Robocup World Competition 2013

WMR will be competing at the World competition, aiming to win Best in the World. As the only UK team to attend, this provides a unique opportunity to promote WMR, Warwick University and UK engineering.

5 Conclusion

The key benefits include potential for commercialisation to assist in saving lives, knowledge and experience gained by students, academics and the wider society and increased publicity through competing in the World RoboCup competition. These are hard to quantify into monetary terms. When the total cost of £54,821.59 is considered, WMR feel the progress made from last year is high enough to justify these costs.

6 References

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7 Appendices

7.1 Appendix A – SWOT Analysis of the 2012 WMR rescue robot design

Strengths	Weaknesses

• Mobility:
  ○ Best in Class award received in 2012 German Open RoboCup
• Arm:
  ○ Strong and stable design, capable of manipulating the head to perform tasks at the competition
• Advanced sensors:
  ○ Investment already made
  ○ Enable scoring extra points in the competition
• Safety:
  ○ Emergency stop performs reliably
	• Difficult to control:
	  ○ Arm can only be controlled in joint mode – slow and takes practise
	  ○ Graphical User Interface (GUI) is poorly laid out and displays very little information
	  ○ Shaky video feedback due to vibrations in arm and head
	  ○ No feedback to the operator station from the batteries
	• Poor reliability:
	  ○ Front and rear cameras as well as the head servos sometimes fail to power up
	  ○ IR camera and CO_2 sensor wired up but non-functional
	  ○ Difficult to access electronics for maintenance
	• Safety:
	  ○ Batteries difficult to connect and disconnect

Opportunities	**Threats**

• Existing sensors and devices:
  ○ Hokuyo LiDAR and XSens inertial measurement unit can be used to attempt arena mapping or provide feedback to the operator
  ○ Existing gripper can be attached
• Software development:
  ○ GET-bot Collaboration
  ○ Inverse Kinematics
• Operator warnings:
	• Electronics:
	  ○ Unpredictable failures at power-up of various sensors and devices
	  ○ Undocumented wiring, lack of colour coding or labelling
	  ○ Poorly done wiring and connectors
	• Mechanical:
	  ○ Damaged chassis parts (flipper brackets)
	  ○ Damaged motors

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Tip prevention
Battery monitoring system

Readiness:

Testing in Remotec assault course
Increased ruggedness - waterproofing, dustproofing

Project Management:

Attract sponsorship due to higher profile competition
Learn from Remotec experience in designing bomb disposal robots

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Worn tracks

Software:

Poorly documented code impeding software development

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7.2 Appendix B – Reassignment of tasks following M. Truscott's leaving

On the 11/01/13 M. Truscott announced that he will be leaving the team with immediate effect. All tasks in the Gantt chart that were assigned to him at that point were either cancelled or reassigned (Table 5).

Table 5. Reassignment of M. Truscott's tasks.

Task	Status	Comments
UML Diagram and restructuring of the software architecture	Cancelled	This time consuming task will not be carried out. Instead local clean-up will be performed on an as-needed basis
One click start-up	Cancelled	While an important feature for ease of use of the robot, this is not critical
Fixing IR camera interface	Reassigned to Edgars Zauls	**High Priority** as this is crucial for scoring points in the competition
Flipper and motor encoder feedback	Reduced scope and reassigned to Kris Buckstone	**High Priority** as this is crucial for improved operator awareness. Feedback to GUI now only required from flipper encoders.
Implementing "heartbeat"	Cancelled	While a useful feature, this is not critical. Implementation is likely to be difficult without restructuring the software first
Implementing LIDAR interface	Reassigned to Edgars Zauls	Low Priority. This can be accomplished relatively easily by using existing code. Raw LIDAR data can then be displayed in the GUI as a driving aid
Implementing Xsens interface	Reassigned to Kris Buckstone	Low Priority. Re-use of existing code permits yaw, pitch and roll information to be integrated with robot 3D representation in the GUI
Investigate appropriate SLAM techniques	Cancelled	Due to time constraints and the considerable complexity of the task
Investigate LIDAR and IR based autonomy	Cancelled	Due to time constraints and complexity. This also lowers the workload for Nick developing head electronics

7.3 Appendix C – Total Material Costs

Chassis	18mm Steel Bars	£13.00
	Metal for body	£72.00
	Bearings	£19.20
	Bay Plastics	£626.33
	HPC gears	£19.82
	Acrylic for electronic brackets from Gilbert Curry Ind Plastics	£37.00
	New Motor	£380.11
	Angle Bracket	£4.74
	Water jetting	£85.66
	Grub screws	£8.12
	TOTAL	**£1,265.98**
Power System	Traco Power Supplies	£220.05
	Power Boards	£976.68
	I^2C switch	£2.03
	Mouser order	£618.98
	Mouser order	£30.39
	Mouser order	£331.19
	TOTAL	**£2,179.32**
Sensors and Devices	CO2 board	£10.00
	Flipper Encoders	£25.44
	Rapid Prototyping	£576.98
	Panel mount USB cable	£6.40
	TOTAL	**£618.82**
Control System		£0.00
Testing		£0.00
Miscellaneous	Board pens and duct tape	£3.97
	T-shirts and stickers	£197.50
	TOTAL	**£201.47**
Travel Budget	Competition Entry Fees	£1,880.00
	Transport	£950.00
	Accommodation	£1,100.00
	Food Expenses	£570.00
	TOTAL	**£4,500.00**
	GRAND TOTAL	**£8,765.59**

7.5 Appendix D – Full Gantt Chart

Notes:

- One day in the Gantt chart corresponds to 2 hours of working time. This is due to the fact that the project should account for 25% of student final year working time (and assuming 8 hour working day)
- Technician time included in the Gantt chart only accounts for consultations. Actual manufacturing time has been recorded by WMG workshop management in the job request system.

7.6 Appendix E – Cost for re-manufacture

Component	Cost (£)	Part Number	Supplier
Chassis			
Metal for chassis space frame	72		Ravenace Metals
Water Jetting for chassis space frame	80		AquaJet
Electronics			
Flipper Encoders	25.13		Future Electronics
CO_2 Board	10		Custom design, in-house
Power distribution board	400		Custom design, in-house
Battery monitoring system	200		Custom design, in-house
RX64 Servo, Robotics USB2 Dynamixel -PC interface	441.65		Robotis
Melexis rotational position sensor	41.48	MLX90316	Melexis
Connectors			Harwin
Wire - Single Conductor 24AWG 7/32 in various colours	134.05 (7 wires x 19.15)	602-6712-100-xx (where xx depends on colour)	Overclockers UK
AX3500 4 x 60A DC Motor Controller	654.89	AX3500	Active Robots
Startech 4 Port USB To Serial Adapter Hub - With COM Retention	44.88	161457	www.ebuyer.com
Axis M1054 HD IP network camera x 2	538 (£269 x 2)	0338-003	www.networkwebcams.co.uk
ASUS RT-N56U router	82.54	RT-N56U	http://www.systo.co.uk/
Dynamixel Robotics RX-64 Servo	180.50	HN05-N101	http://robosavvy.com
Flir Photon 160 Infrared Sensor	2,522.90	427 (historic part, purchased in 2008)	Flir

HOKUYO Robotics Laser Range Finder	1522.54	URG-04LX	Active Robots
Intel DG45FC LGA775 Media Series Mini-ITX Mainboard	95	DG45FC	http://linitx.com/
Mechanical			
18mm silver steel bars	13		Ravenace Metals
Bearings	19.20		SKF
38mm ID Carbon fibre tube (roll wrapped) 0.5M for arm	110.97		Easy Composites
Double bossed Anti-backlash Worm Gear	160.21		HPC Gears Ltd
1500 x 333mm Tool Steel Bar	5.89		Ravenace Metals
50 Tooth Anti backlash Worm Gear Express	215.27		HPC Gears
4mm Ball Bearings	8.95	QFT-671-1004D	GTSS
2 x 940x50mm T10V Endless Belt	82.10	ZP40BS (historic part, purchased in 2008)	Brammer UK Ltd
2 x 1100x75mm T10V Endless Belt	125.64	ZP40BS (historic part, purchased in 2008)	Brammer UK Ltd
Motor: RE50 (370354) Gearbox: GP52C 4.3/1 (223081) Encoder: 110518 x 2	687.88	RE50	Maxon Motor
Motor: RE35 (273754) Gearbox: GP52C (223111) Encoder: 110514	325.77	RE35	Maxon Motor
Motor: RE30 (310007) Gearbox: GP32C 23/1 (166936X) Encoder: None x 3	697.95	RE30	Maxon Motor
Motor: AMAX26 (11940) Gearbox: GP32C 246/1 (166949) Encoder: None	193.50	AMAX26	Maxon Motor
Rapid Prototyping (head and	570		Dr Greg Gibbons from WMG,

battery cases)			University of Warwick
Shell x 2 made from ABS	630		Bay Plastics Ltd
Lithium Polymer Batteries (x4)	180 (4 at £45 each)		Various suppliers
TOTAL: £10,937.84			