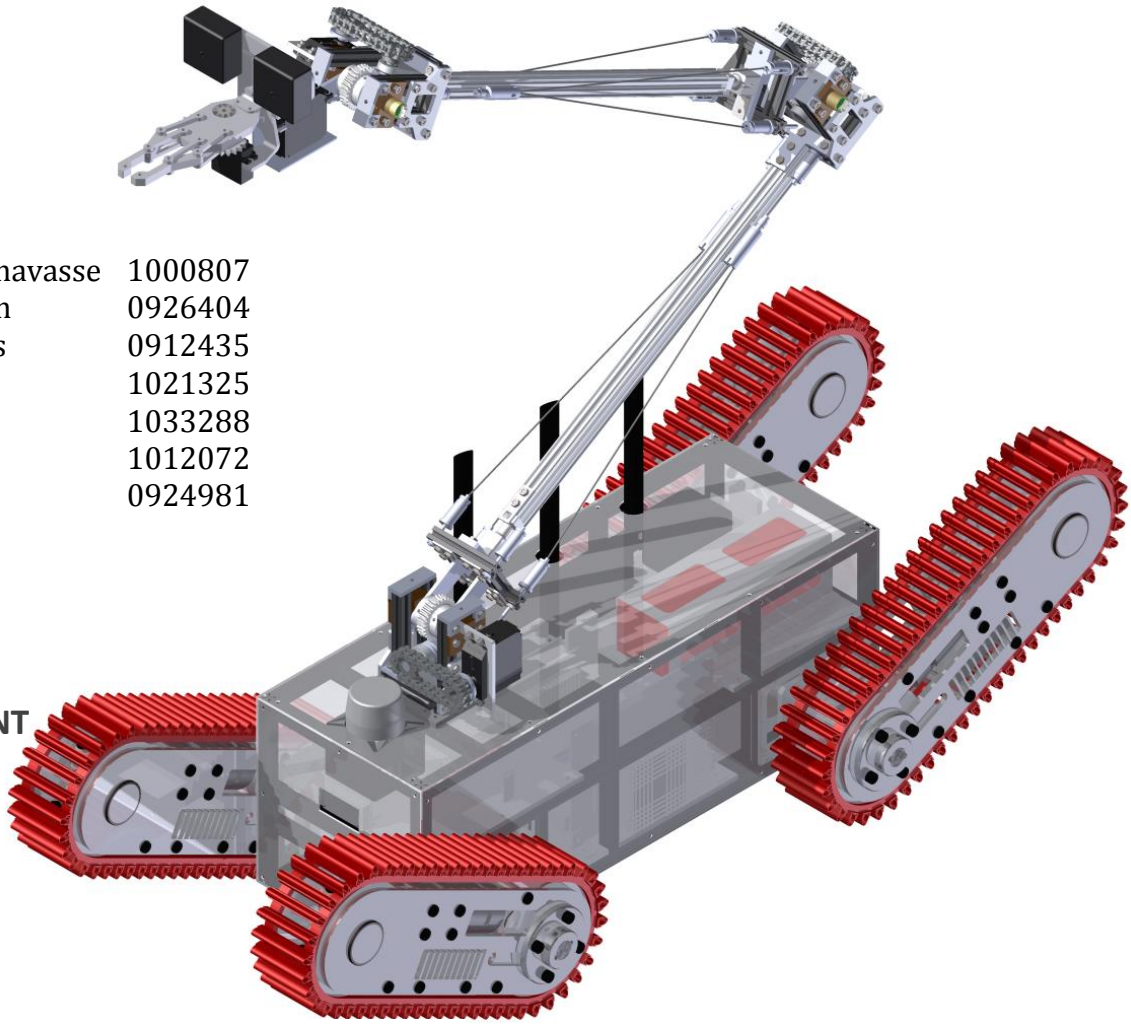
Warwick Mobile Robotics

THE UNIVERSITY OF WARWICK

Urban Search and Rescue Robotics

Cost Benefit Analysis Report



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WMG Innovative Solutions

CATAPULT High Value Manufacturing

School of Engineering

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Contents

Chapter 1. Introduction

The Warwick Mobile Robotics (WMR) team designed, manufactured and built a new small, light Urban Search and Rescue (USAR) robot (Figure 1), upgraded WMR's existing robot (Figure 2), and took both to the RoboCup German Open competition to assess their capabilities. The costs incurred throughout the project are evaluated with regard to the benefit to students, the university, and wider society.

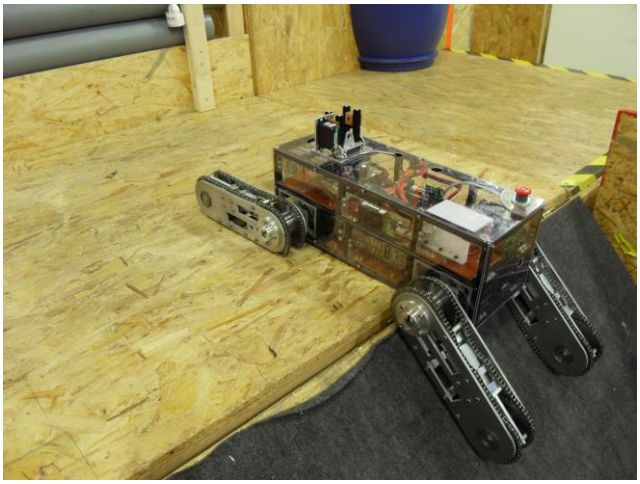

Figure 1 - New Robot Posing at the Top of the 45⁰ Slope

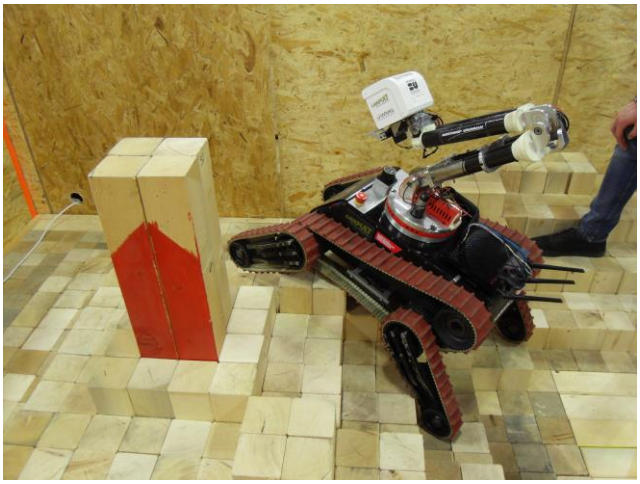

Figure 2 - Old Robot Competing on the Step Field

Chapter 2. Aims and Objectives

1. Improve the existing robot:
    a. Upgrade/enhance the existing USAR robot
    b. Operator training to allow comprehensive robot control
2. Develop a smaller USAR robot capable of searching for simulated victims in a small confined disaster environment with the following core development aims:
    a. A core modular architecture that allows the platform to be easily modified
    b. Low cost, lightweight and deployable by one person
    c. Design with key features such as reliability, reparability and maintainability
    d. Introduce mapping capabilities to aid the robot in becoming fully autonomous
    e. Optimise Human Machine Interface (HMI) to aid operator awareness
    f. Allow future teams to develop this prototype towards a commercially viable design
3. Enter the RoboCup German Open 2014 in the “Rescue” category utilising both robots

Chapter 3. Work Undertaken

The work undertaken was divided between the existing robot and the new robot.

3.1. Existing Robot

The existing USAR robot was maintained to retain current capabilities rather than upgrading them as the new design was prioritised. Table 1 discusses the issues identified with the robot and corresponding solutions.

Table 1 - Maintenance Tasks on Old Robot

No.	Issue	Solution
1	Rear flipper motor burnt out	Motor and gearbox replaced and axle bearing realigned to stop axle bending, preventing additional strain on the motor.
2	Arm's wrist motor burnt out	The motor was replaced and a torque limiting setting was introduced to help prevent future damage.
3	Disorganised internal wiring	Unused wires were removed and cable tidies were used to arrange existing wiring.
4	Single webcam cannot be used with 3D headset	The network camera (118g) was replaced with two lightweight webcams (10g total) and a new 3D printed head plate was made to secure them.
5	Rear view camera damaged	The camera was replaced maintaining this capability.

3.2. New Robot

Due to its size and mass, the new robot allows access to smaller environments and can be deployed by one person. The work undertook included:

3.2.1. Chassis

An innovative chassis was produced using extruded aluminium beam, tufnol, water-jet cut aluminium plates, stainless steel brackets and a polycarbonate shell (Figure 3 and Figure 4). This highly adaptable design allows internal components to be packaged efficiently into the chassis, and its size to be modified.

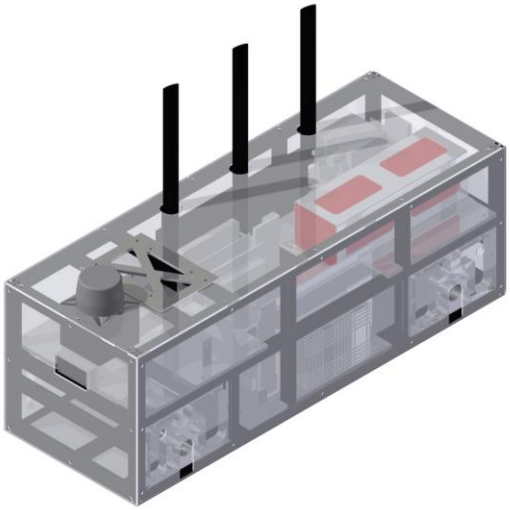

Figure 3 – Final CAD Chassis Design with Shell

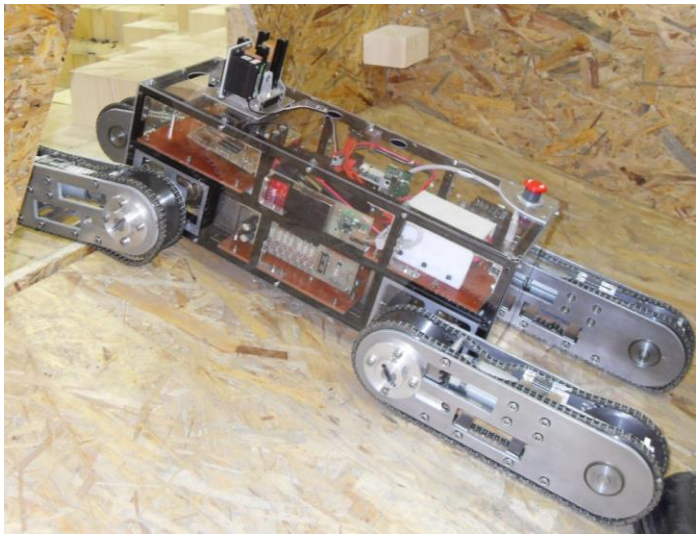

Figure 4 – Final Chassis Assembly

3.2.2. Drivetrain

An innovative drivetrain was produced incorporating drive motors and controllers inside each track unit to save space and reduce heating within the chassis. To maximise mobility whilst reducing mass and cost, a design with two pairs of flipper units (with 360^0 rotation) (Figure 5). Removing the fixed middle track unit found previously (Figure 6) allowed width and mass to be reduced.

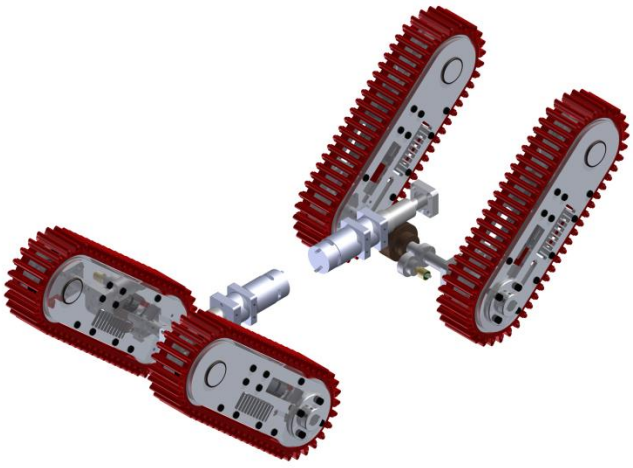

Figure 5 - New Drive Train Consisting of Two Sets of Flippers and Tracks with Enclosed Motors

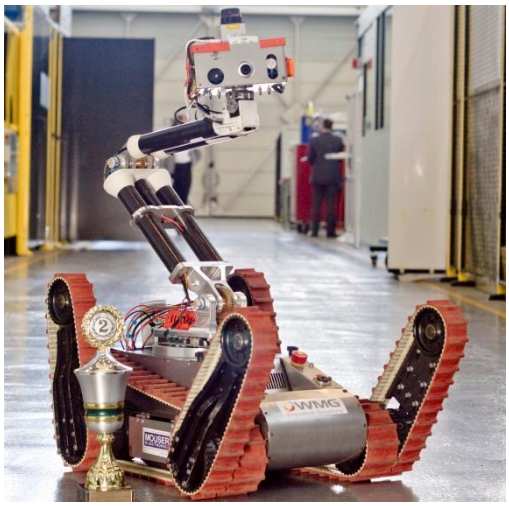

Figure 6 - Old Robot Style with Fixed Tracks and Flippers, Adding Width and Mass

3.2.3. Arm

An innovative modular arm design was produced (Figure 7) using identical joints constructed from off-the-shelf extruded aluminium beam. The design has significantly lower mass and cost than the previous design (Figure 8).

Figure 7 - 2014 Mechanical Arm Design

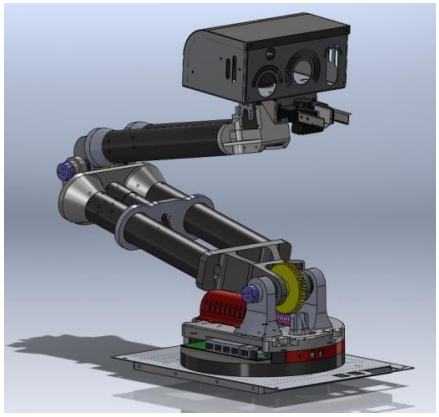

Figure 8 - 2012 Mechanical Arm Design

3.2.4. Head and Gripper

A head was designed (Figure 9) to house two cameras. A modified off-the-shelf gripper was selected capable of manipulating objects up to 100mm wide and up to 1kg. The complete design is 57% lighter than previous designs (Figure 10).

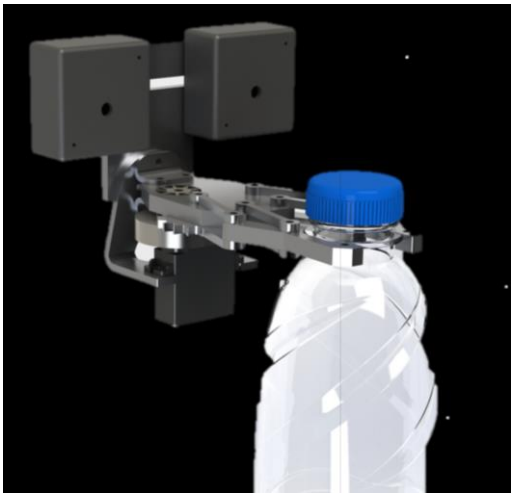

Figure 9 - 2014 Head and Manipulator Design

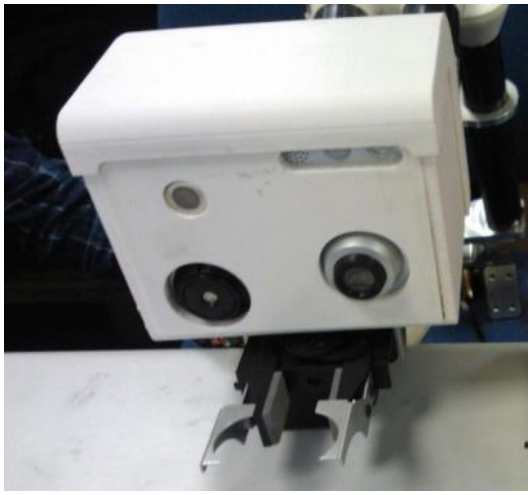

Figure 10 - 2012 Head and Manipulator Design

3.2.5. Power Distribution

Two power distribution boards were designed and manufactured (Figure 11). Switchable outputs allow devices to be turned off to conserve power. The existing board (Figure 12) was too large for the new chassis and supplied the wrong voltages.

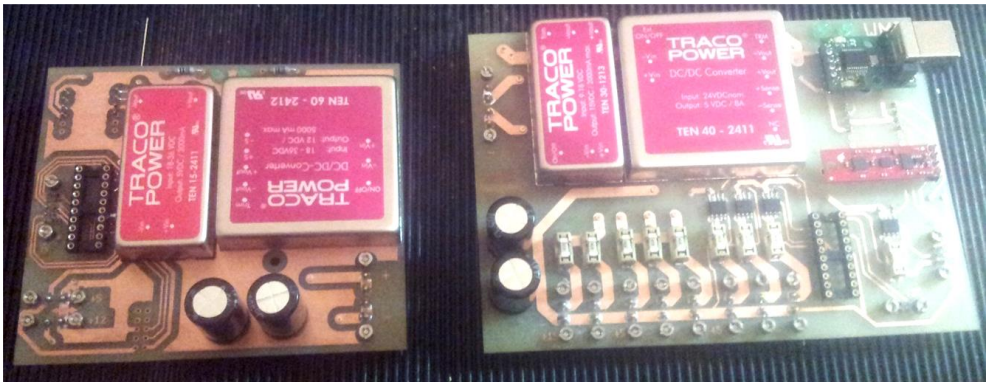

Figure 11 – Arm Power Board (Left) and Main Power Board (Right)

Figure 12 - 2012/13 Power Board Design

3.2.6. Battery Monitoring

A battery monitoring circuit was simulated but was not constructed or tested.

3.2.7. Control Electronics

A modular electronic architecture was designed allowing plug and play systems to function independently of each other.

3.2.8. Software

Software was designed using Robot Operating System (ROS) to remotely control the robot and display system, and sensor data. Testing was conducted on the existing robot including mapping (Figure 13) and 3D augmented reality vision with intuitive head tracking (Figure 14 and Figure 15) to improve operator's situational awareness.

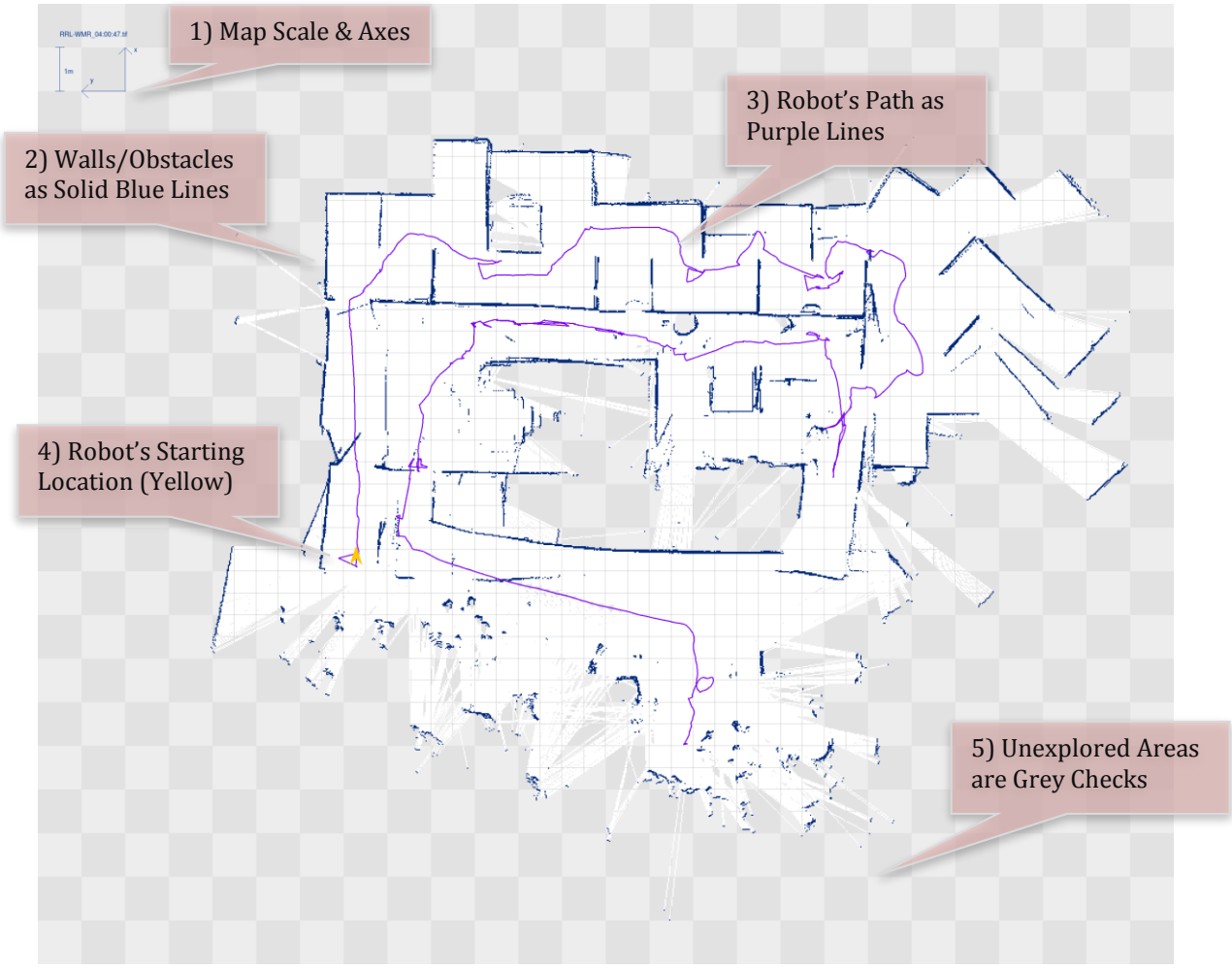

Figure 13 - Map Produced by the WMR Robot at the 2014 RoboCup Rescue Competition (Magdeburg, Germany)

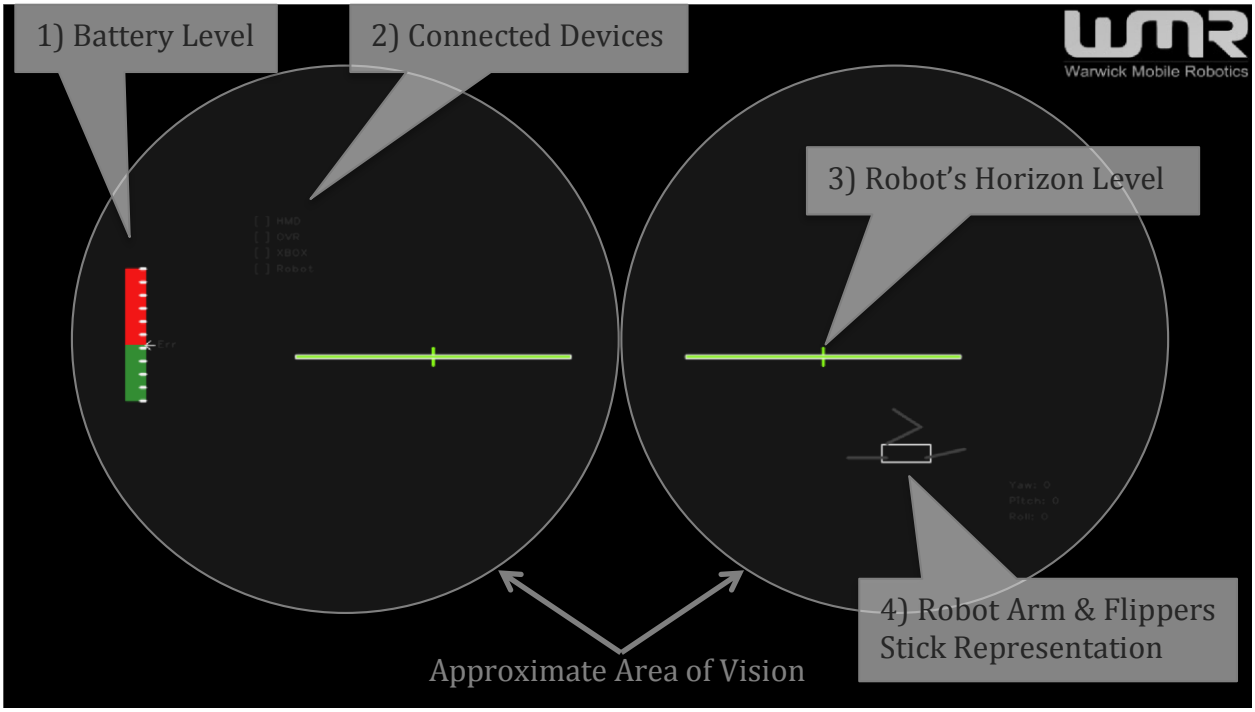

Figure 14 - Augmented Reality 3D Heads-up Display on the Oculus Rift Showing the View from the Left and Right Eye

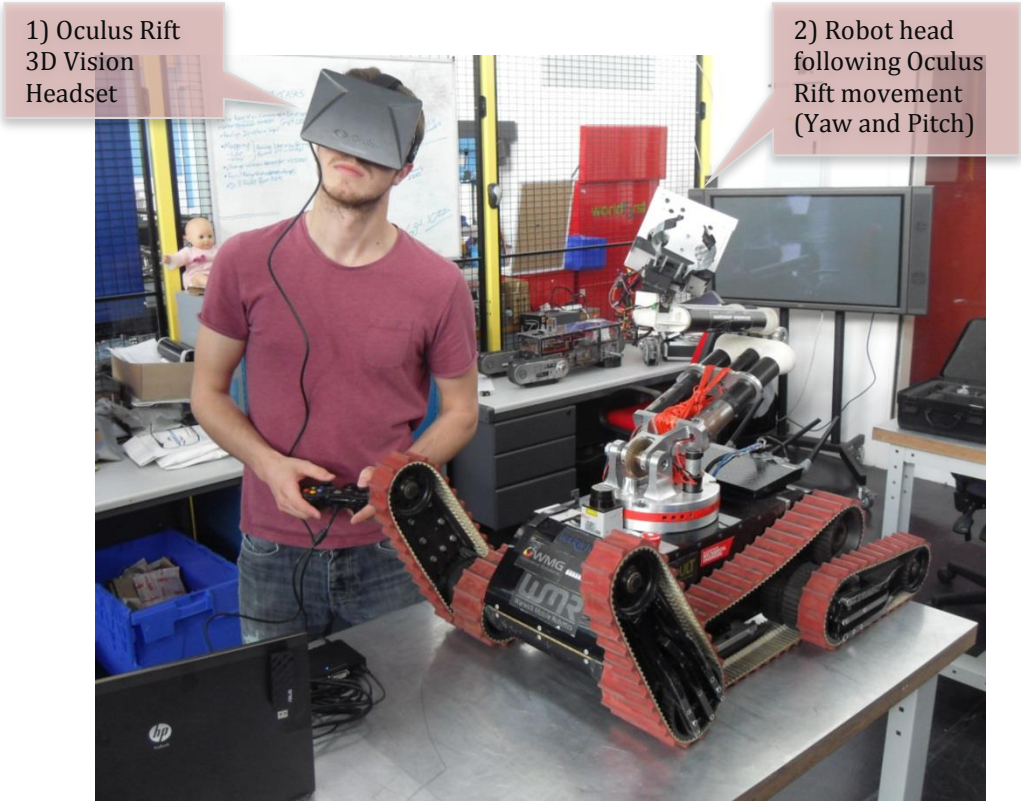

Figure 15 – Robot's Head Mapped to Operator's Head Movement

Chapter 4. Cost and Benefit Analysis

4.1. Project Costs

The full cost of the project totalled £68,348.69. This includes materials, off-the-shelf components, postage, competition and labour.

Figure 16 provides a high level indication of the expenditure relative to the aims and objectives.

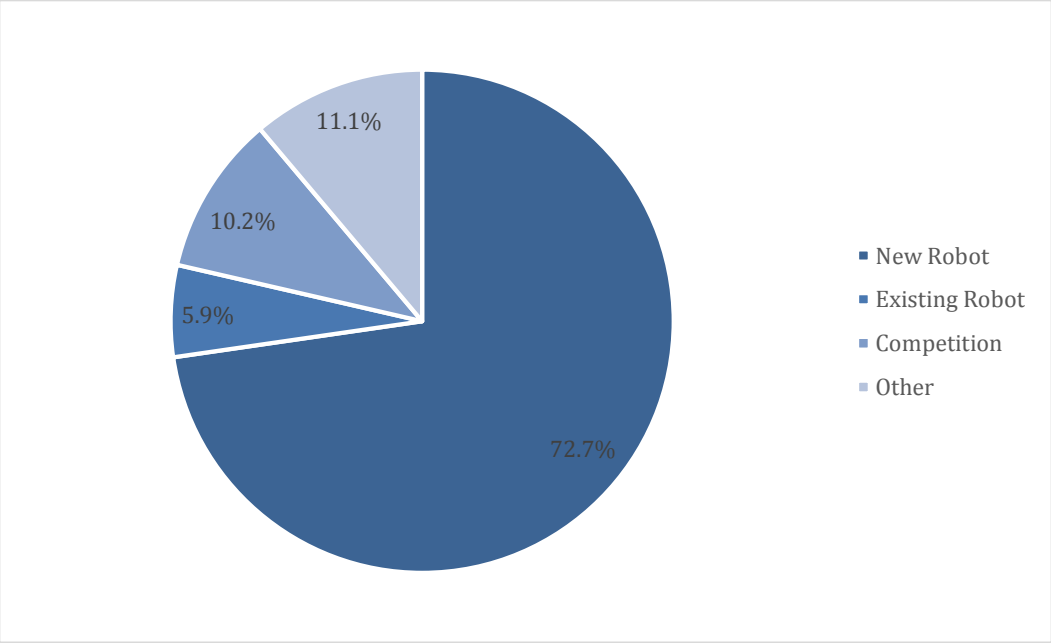

Figure 16 - Breakdown of Full Project Costs

4.1.1. New Robot Development Costs

Table 2 shows that the total development cost for the new robot was £5,849.32. This includes the material costs as well as spare components used for testing and repair.

Table 2: Breakdown of New Robot Development Costs

Sub-System	Cost (£)	% Total Cost
Chassis	1,364.23	23.3
Drivetrain	2,504.98	42.9
Arm System	1,404.18	24.0
Other	571.93	9.8
Total	£5,845.32	

The material cost for the robot was £4,264.04. A full breakdown is in Appendix D.

4.1.2. Existing Robot Maintenance Costs

14% of the project's material costs were spent on maintaining the existing robot (£984.36).

4.1.3. Competition Costs

Table 3 shows the total competition costs to be £3,134.01.

Table 3: Competition Cost Breakdown

Expense	Cost (£)
Team Entry Cost	680.00
People Carrier Hire	759.60
Fuel	235.02
Ferry	190.90
Accommodation (5 nights)	799.00
Food	469.49
Total	£3,134.01

4.1.4. Labour Costs

Table 4 shows the total labour costs to be £58,346.75.

Table 4: Breakdown of Labour Costs

Cost Category	Cost/hr	Individual	Hours	Cost (£)
Director	£75	Peter Jones	22	1,650.00
		Emma Rushforth	22	1,650.00
Academic	£75	Peter Kimber	1	75.00
Student	£15	Christopher Chavasse	609	9,131.25
		Andrew Parkin	579	8,677.50
		Trevor Whales	482	7,222.50
		Lauren Rutter	370	5,542.50
		James Yardley	364	5,460.00
		Vishal Dhanji	305	4,570.50
		Jannah Aljafri	379	5,677.50
Technician	£30	Carl Lobjoit	218	6,540.00
		Paul Johnson	5	150.00
		School of Eng. Technicians	15	450.00
		Electrical Technicians	5	150.00
External Support	£50	Stefan Winkvist	15	750.00
		Edgar Zauls	13	650.00
			Total Cost	£58,346.75

Table 5 shows the breakdown of student labour by sub-system and non-technical tasks. This data was collected via weekly timesheets completed by students (example in Appendix A).

Table 5: Breakdown of Student Labour by Sub-System and Tasks

Sub-System/ Task	Hours	Cost (£)	% Total Cost
Chassis	306	4590	11.3
Drivetrain	218	3270	8.1
Arm System	625	9375	23.2
Electronics and Software	718	10770	12.5
Construction	228	3420	8.4
Project Management	339	5085	12.5
Sponsorship and Publicity	95	1425	3.5
Competition	258	3870	9.5
Finance	74	1110	2.7
Old Robot Maintenance	203	3045	7.5
Other	24	360	0.9
Total	2708	40620	

A Gantt chart was used to plan the project's activities (Appendix B), summarised by Figure 17.

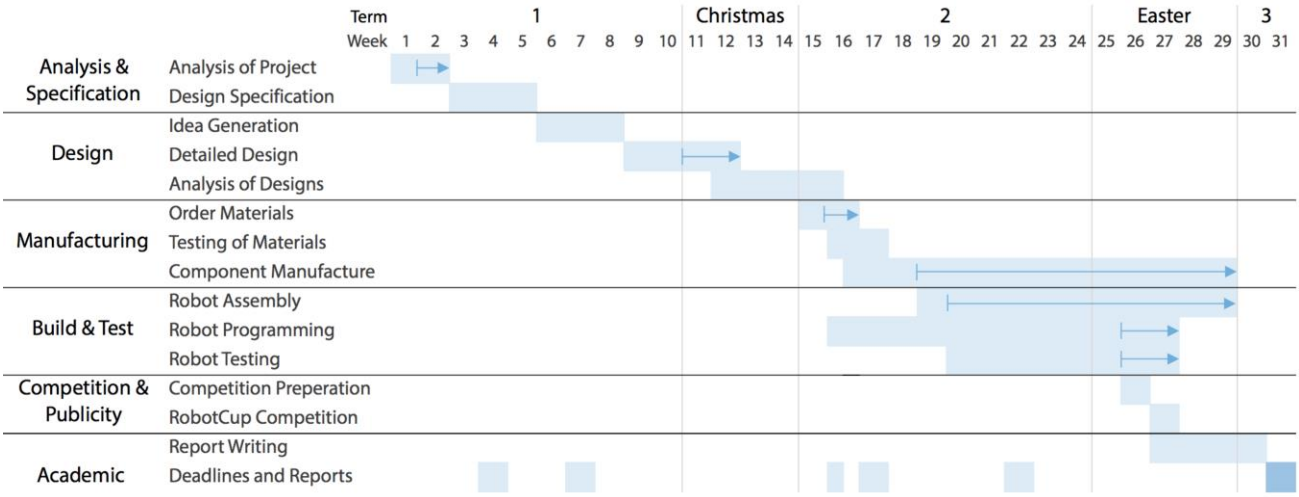

Figure 17 - Summary Gantt Chart (Arrows indicate slippage)

Figure 18 illustrates the progression of the activities performed over the duration of the project.

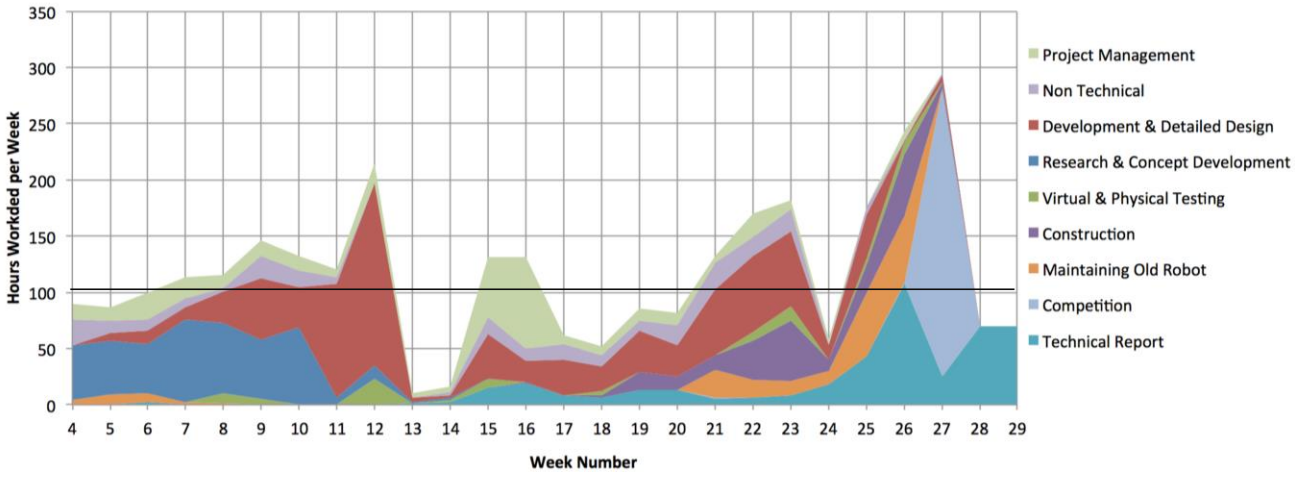

Figure 18 - Weekly Task Distribution

The black line in Figure 18 indicates the average weekly hours. The noticeable peaks are week 12 to meet the manufacturing design deadline, and week 26 for the RoboCup Rescue competition.

4.2. Cost Analysis

Table 6 details the total cost of each sub-system combining the material and labour costs where applicable.

Table 6: Breakdown all Total Costs by Sub-System/Task

Sub-System/ Task	Material Cost (£)	Labour Cost (£)	Total Cost (£)	% Total Cost
Chassis	1364.23	4590.00	5954.23	8.7
Drivetrain	2504.98	3270.00	5774.98	8.5
Arm System	1404.18	9375.00	10779.18	15.8
Electronics and Software	n/a	10770.00	10770.00	15.7
Other[1]	571.93	12425.00	12996.93	19.0
Old Robot Maintenance	984.36	3045.00	4029.36	5.9
Project Management	n/a	5085.00	5085.00	7.4
Assembly and Testing	n/a	3420.00	3420.00	5.0
Sponsorship and Publicity	n/a	1425.00	1425.00	2.1
Competition	3,134.01	3870.00	7004.01	10.3
Finance	n/a	1110.00	1110.00	1.6
Total	£9,963.69	£58,385.00	£68,348.69	

[1] This includes labour costs of non-team members

A battery monitoring circuit was simulated but did not reach a level where it met the specification and could be manufactured. Therefore, the £5677.50 labour expenditure cannot be justified.

The legacy cost incurred maintaining the existing robot was 5.9% of the total project cost. This was to maintain WMR's robotic platform capabilities which have been proven through its successful participation at the RoboCup German Open.

Significant progress was made in the manufacture and construction of the new robot, however it was not fully completed within the timescale. The partial manufacture allowed the new design to be critically evaluated at the RoboCup competition against its potential capabilities and associated cost. Major design lessons were learnt from this process, which will be passed onto future teams adding significant value. The total labour cost for sponsorship and publicity was £1425.00. The team managed to acquire £11,045.39 in sponsorship and donations (Figure 19). Appendix C details these contributions.

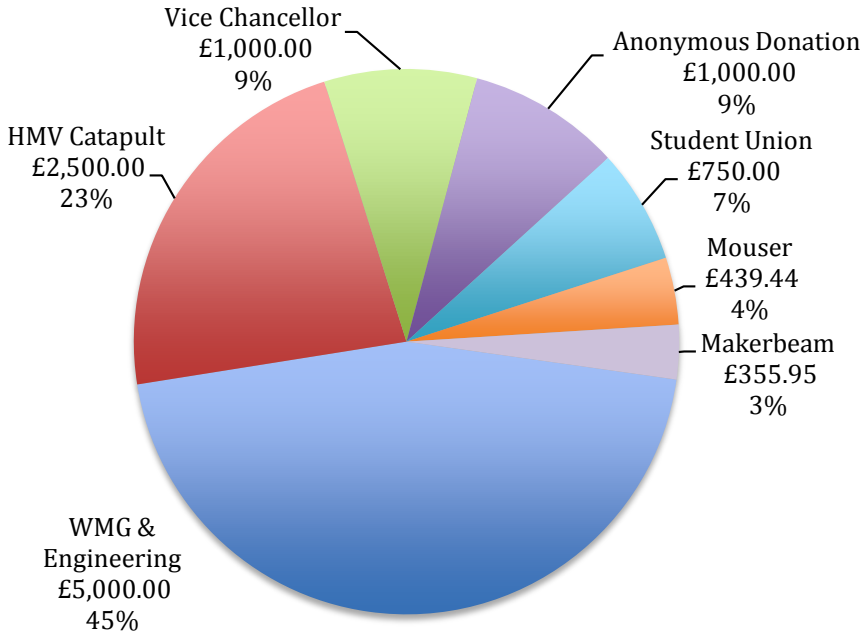

Figure 19 - Breakdown of Sources of Funding

During the year, WMR featured in *The Boar* (Skoulding, 2014). However, the team did not maximise their opportunities to publicise the new innovations.

4.3. Project Benefits

4.3.1. Students

- Development of expertise in robotic engineering allows students to pursue employment or further study in related fields
- Experience of collaboration in a multi-disciplinary team
- Experienced a significant proportion of the product development process from specification to construction.
- Construction phase provided the opportunity for development of machining skills
- Developments of professional skills such as negotiation, organization, time management and administration
- Experience of managing external suppliers and sponsor relationships
- An improved appreciation of resources such as money and labour
- New innovative project with significant scope for development for future students

4.3.2. University

- Having identified that the School of Engineering uses WMR as a significant part of their student recruitment strategy, innovative technologies such as Oculus Rift were implemented to continue to attract prospective students
- Student profiles were produced for university publicity material
- Four of the team travelled to Germany and competed in the RoboCup German Open with the existing robot coming 4th overall (out of 9) and 2nd in mobility

- Developed opportunities for future research collaborations with other universities at the competition
- Maintained and developed new relationships with sponsors, including organisations within the university, which can be utilised in future years
- Potential for the project to be used in the development of educational content to support course material (e.g. ES4A1 Advanced Robotics)

4.3.3. Society

- Published technical reports to aid the development of USAR robots by other researchers
- Encouraged secondary school students to peruse engineering careers at WMG and School of Engineering open days
- Where reuse of robotics systems cannot be guaranteed, commercial costs should not exceed £10,000 (Sellafield, (Winkvist, 2013)). By developing a low cost USAR robot, this barrier to use is removed.
- Developed a robot that can access smaller disaster environments
- Developed a robot that can be used as a research platform
- Used a 3D vision system with head tracking to increase operator's awareness

Chapter 5. Conclusion

A new, innovative USAR robotic platform has been designed and developed. Its features enable future teams to progress towards a smaller, lighter and lower cost robot design suitable for commercial applications. The total cost of the project was £68,348.69, which includes the existing robot, new robot and costs associated with the RoboCup competition. The manufacture of the new robot (although only partially complete and therefore not used) allowed the design to be critically evaluated. This added significant value to future teams for areas to investigate. The project has provided substantial benefits to students, the university and wider society. These include personal development of the team, aiding the university in the recruitment of prospective students, and contributing to the development of innovative search and rescue solutions, ultimately saving lives.

Chapter 6. Bibliography

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[Accessed 1 November 2013].

Appendices

Appendix A – Example Timesheet

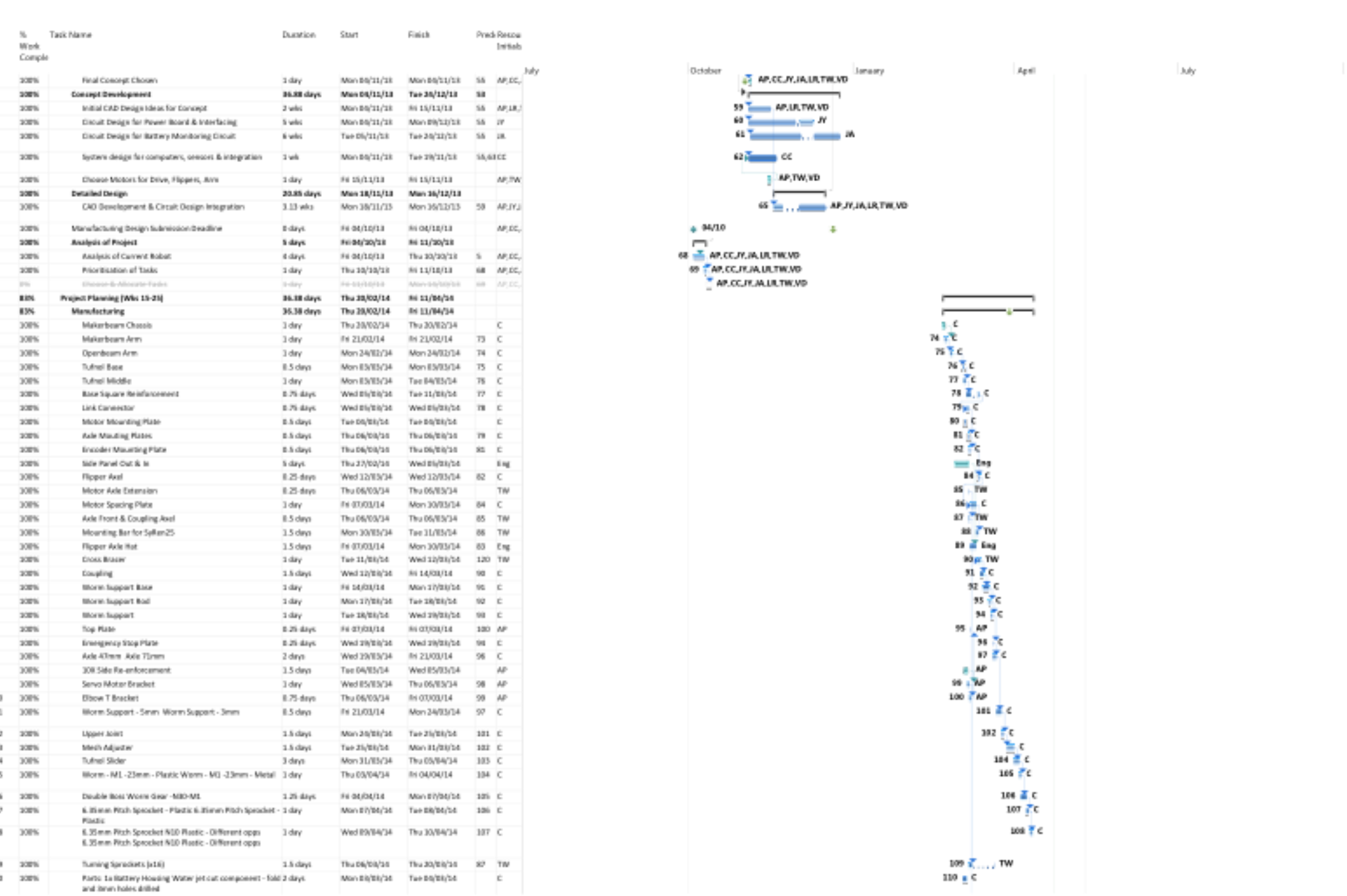
Sheet Owner:	WMR
Hours Worked:	Saturday 08/02/14 - Friday 14/02/14
Submission Deadline:	Friday 14/02/14 - 5pm
Total Hours Worked:	29.5

Date	No. of Hours	Activity Type	Activity Description
10/02/2014	5.0	Maintaining Old Robot	Disassembly of Robot - Found problem with burnt out motor - Took steps to find replacement
10/02/2014	1.0	Individual Meeting	Meet with AP to discuss encoders
11/02/2014	4.0	Report	Continue to write up software section for technical report
11/02/2014	1.0	Competition	Plan journey to RoboCup German Open Competition
12/02/2014	1.5	Other	Help at open day in WMG
12/02/2014	4.0	Design	Programming Robot (SLAM Mapping)
13/02/2014	1.0	Group Meeting	Weekly meeting with project directors
13/02/2014	4.0	Design	Updating new WMR laptop & continuing work on old robot
13/02/2014	1.0	Non-Technical Role (e.g. Sponsorship)	Writing Student Profile
14/02/2014	2.0	Construction	Mock up mount for two head cameras for testing with Oculus Rift
14/02/2014	5.0	Design	Work on streaming footage from both cameras to Oculus Rift head set, and implementing a HUD on top of the footage

Activities were defined from drop down menus.

Appendix B – Full Gantt Chart

% Work Complete	Task Name	Duration	Start	Finish	Predecessors	Resource Initials
100%	Final Concept Chosen	1 day	Mon 04/11/13	Mon 04/11/13	55	AP,CC,
100%	**Concept Development**	**36.88 days**	**Mon 04/11/13**	**Tue 24/12/13**	**58**	
100%	Initial CAD Design Ideas for Concept	2 wks	Mon 04/11/13	Fri 15/11/13	55	AP,LR,
100%	Circuit Design for Power Board & Interfacing	5 wks	Mon 04/11/13	Mon 09/12/13	55	JY
100%	Circuit Design for Battery Monitoring Circuit	6 wks	Tue 05/11/13	Tue 24/12/13	55	JA
100%	System design for computers, sensors & integration	1 wk	Mon 04/11/13	Tue 19/11/13	55,63	CC
100%	Choose Motors for Drive, Flippers, Arm	1 day	Fri 15/11/13	Fri 15/11/13		AP,TW
100%	**Detailed Design**	**20.85 days**	**Mon 18/11/13**	**Mon 16/12/13**		
100%	CAD Development & Circuit Design Integration	3.13 wks	Mon 18/11/13	Mon 16/12/13	59	AP,JY,J
100%	Manufacturing Design Submission Deadline	0 days	Fri 04/10/13	Fri 04/10/13		AP,CC,
100%	**Analysis of Project**	**5 days**	**Fri 04/10/13**	**Fri 11/10/13**		
100%	Analysis of Current Robot	4 days	Fri 04/10/13	Thu 10/10/13	5	AP,CC,
100%	Prioritisation of Tasks	1 day	Thu 10/10/13	Fri 11/10/13	68	AP,CC,
0%	Choose & Allocate Tasks	1 day	Fri 11/10/13	Mon 14/10/13	69	AP,CC,
83%	**Project Planning (Wks 15-25)**	**86.38 days**	**Thu 20/02/14**	**Fri 11/04/14**		
83%	**Manufacturing**	**35.38 days**	**Thu 20/02/14**	**Fri 11/04/14**		
100%	Makerbeam Chassis	1 day	Thu 20/02/14	Thu 20/02/14		C
100%	Makerbeam Arm	1 day	Fri 21/02/14	Fri 21/02/14	73	C
100%	Openbeam Arm	1 day	Mon 24/02/14	Mon 24/02/14	74	C
100%	Tufnol Base	0.5 days	Mon 03/03/14	Mon 03/03/14	75	C
100%	Tufnol Middle	1 day	Mon 03/03/14	Tue 04/03/14	76	C
100%	Base Square Reinforcement	0.75 days	Wed 05/03/14	Tue 11/03/14	77	C
100%	Link Connector	0.75 days	Wed 05/03/14	Wed 05/03/14	78	C
100%	Motor Mounting Plate	0.5 days	Tue 04/03/14	Tue 04/03/14		C
100%	Axle Mauting Plates	0.5 days	Thu 06/03/14	Thu 06/03/14	79	C
100%	Encoder Mounting Plate	0.5 days	Thu 06/03/14	Thu 06/03/14	81	C
100%	Side Panel Cut & In	5 days	Thu 27/02/14	Wed 05/03/14		Eng
100%	Flipper Axel	0.25 days	Wed 12/03/14	Wed 12/03/14	62	C
100%	Motor Axle Extension	0.25 days	Thu 06/03/14	Thu 06/03/14		TW
100%	Motor Spacing Plate	1 day	Fri 07/03/14	Mon 10/03/14	84	C
100%	Axle Front & Coupling Axel	0.5 days	Thu 06/03/14	Thu 06/03/14	65	TW
100%	Mounting Bar for Spikes25	1.5 days	Mon 10/03/14	Tue 11/03/14	66	TW
100%	Flipper Axle Nut	1.5 days	Fri 07/03/14	Mon 10/03/14	63	Eng
100%	Cross Brace	1 day	Tue 11/03/14	Wed 12/03/14	120	TW
100%	Coupling	1.5 days	Wed 12/03/14	Fri 14/03/14	90	C
100%	Worm Support Base	1 day	Fri 14/03/14	Mon 17/03/14	91	C
100%	Worm Support Rod	1 day	Mon 17/03/14	Tue 18/03/14	92	C
100%	Worm Support	1 day	Tue 18/03/14	Wed 19/03/14	93	C
100%	Top Plate	0.25 days	Fri 07/03/14	Fri 07/03/14	100	AP
100%	Emergency Stop Plate	0.25 days	Wed 19/03/14	Wed 19/03/14	94	C
100%	Axle 47mm Axle 72mm	2 days	Wed 19/03/14	Fri 21/03/14	96	C
100%	308 Side Re-enforcement	1.5 days	Tue 04/03/14	Wed 05/03/14		AP
100%	Servo Motor Bracket	1 day	Wed 05/03/14	Thu 06/03/14	98	AP
100%	Elbow T Bracket	0.75 days	Thu 06/03/14	Fri 07/03/14	99	AP
100%	Worm Support - 5mm Worm Support - 3mm	0.5 days	Fri 21/03/14	Mon 24/03/14	97	C
100%	Upper Joint	1.5 days	Mon 24/03/14	Tue 25/03/14	101	C
100%	Mech Adjuster	1.5 days	Tue 25/03/14	Mon 31/03/14	102	C
100%	Tufnol Slider	3 days	Mon 31/03/14	Thu 03/04/14	103	C
100%	Worm - M1 -23mm - Plastic Worm - M1 -23mm - Metal	1 day	Thu 03/04/14	Fri 04/04/14	104	C
100%	Double Boss Worm Gear -M80-M1	1.25 days	Fri 04/04/14	Mon 07/04/14	105	C
100%	6.35mm Pitch Sprocket - Plastic 6.35mm Pitch Sprocket - Plastic	1 day	Mon 07/04/14	Tue 08/04/14	106	C
100%	6.35mm Pitch Sprocket N10 Plastic - Different opps 6.35mm Pitch Sprocket N10 Plastic - Different opps	1 day	Wed 09/04/14	Thu 10/04/14	107	C
100%	Turning Sprockets (x16)	1.5 days	Thu 06/03/14	Thu 20/03/14	97	TW
100%	Parts 1a Battery Housing Water jet cut component - fold and 3mm holes drilled	2 days	Mon 03/03/14	Tue 04/03/14		C



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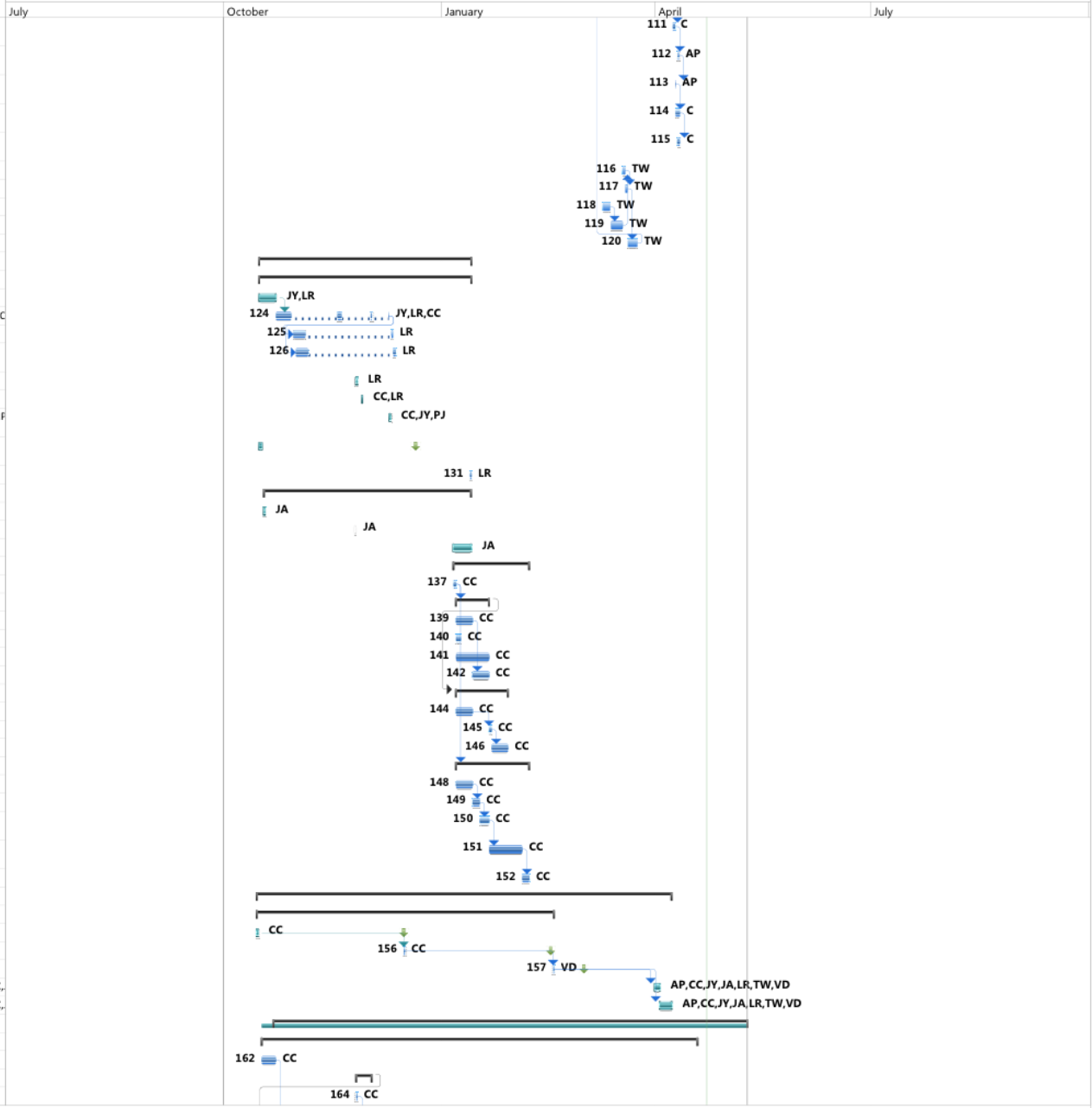
d 23/04/14

Task | Summary | Inactive Milestone | Duration-only | Start-only | External Milestone | Manual Progress
Split | Project Summary | Inactive Summary | Manual Summary Rollup | Finish-only | Deadline
Milestone | Inactive Task | Manual Task | Manual Summary | External Tasks | Progress

	% Work Comple	Task Name	Duration	Start	Finish	Pred	Resou Initials
1	100%	Parts: 2x Side Plate Water jet cut component - 3mm holes drilled	1 day	Tue 08/04/14	Wed 09/04/14	107	C
2	100%	Parts: 1x Bottom Plate Cut to shape and 3mm holes drilled.	0.25 days	Thu 10/04/14	Thu 10/04/14	111	AP
3	100%	Parts: 1x Arm Chassis Mount Water jet cut component - 3mm holes drilled	0.25 days	Wed 09/04/14	Wed 09/04/14	112	AP
4	100%	Parts: 1x Front Plate Water jet cut component - 3mm holes drilled	0.25 days	Wed 09/04/14	Fri 11/04/14	113	C
5	100%	Parts: 1x Back Plate Water jet cut component - 3mm holes drilled	0.25 days	Thu 10/04/14	Fri 11/04/14	114	C
6	0%	Glue Tube into U Channel (Tracks)	1 day	Tue 18/03/14	Wed 19/03/14	119	TW
7	0%	Cut U Channel to Length (Tracks)	1 day	Wed 19/03/14	Thu 20/03/14	116	TW
8	0%	Cut L Channel to Length (Tracks)	2 days	Mon 10/03/14	Wed 12/03/14		TW
9	0%	Glue L Channel to Chain (55/Chain * 8)	3 days	Thu 13/03/14	Tue 18/03/14	118	TW
10	0%	Glue U Channel to L Channel (55 * 4)	2 days	Thu 20/03/14	Mon 24/03/14	117	TW
11	**99%**	**Sponsorship & Publicity**	**63.5 days**	**Wed 16/10/13**	**Mon 13/01/14**		
12	**98%**	**Sponsorship**	**63.5 days**	**Wed 16/10/13**	**Mon 13/01/14**		
13	100%	Update Sponsorship Pack	5 days	Wed 16/10/13	Tue 22/10/13		JY,LR
14	100%	Finalise Sponsorship Pack	1.2 wks	Wed 23/10/13	Mon 09/12/13	123	JY,LR,C
15	50%	Arrange Remotech Visit	3.63 days	Wed 30/10/13	Wed 11/12/13	124	LR
16	100%	Contact Previous Year's Sponsors to Retain Links	1 wk	Thu 31/10/13	Thu 12/12/13	124	LR
17	100%	Confirm Mouser Sponsorship	1 hr	Tue 26/11/13	Tue 26/11/13		LR
18	100%	Meeting with Harwin	1 hr	Thu 28/11/13	Thu 28/11/13		CC,LR
19	100%	Meeting with Nick Mallinson (HMV Catapult)	1 hr	Tue 10/12/13	Tue 10/12/13		CC,JY,P
20	100%	Finalise Sponsorship Deals with Companies	1 day	Wed 16/10/13	Wed 16/10/13		
21	100%	Write to Vice Chancellor	0.5 days	Mon 13/01/14	Mon 13/01/14		LR
22	**100%**	**Publicity**	**61.13 days**	**Fri 18/10/13**	**Mon 13/01/14**		
23	100%	Contact The Boar	1 hr	Fri 18/10/13	Fri 18/10/13		JA
24	0%	~~WMG Academy Publicity Stunt~~	~~1 day?~~	~~Mon 25/11/13~~	~~Mon 25/11/13~~		~~JA~~
25	100%	Contact Local & National Newspapers	1 wk	Mon 06/01/14	Mon 13/01/14		JA
26	**100%**	**Software**	**24 days?**	**Mon 06/01/14**	**Thu 06/02/14**		**CC**
27	100%	Define Structure	1 day?	Mon 06/01/14	Mon 06/01/14		CC
28	**100%**	**GUI & User Control Program**	**10 days**	**Tue 07/01/14**	**Mon 20/01/14**	**137**	**CC**
29	100%	Read in Controller Data & Setup Network	5 days	Tue 07/01/14	Mon 13/01/14		CC
30	100%	Define GUI design for Oculus Rift	2 days	Tue 07/01/14	Wed 08/01/14		CC
31	100%	Setup GUI for user to view information	10 days	Tue 07/01/14	Mon 20/01/14		CC
32	100%	Send & Receive "Heartbeat" over Network	5 days	Tue 14/01/14	Mon 20/01/14	139	CC
33	**100%**	**Main Robot Computer Program**	**16 days?**	**Tue 07/01/14**	**Tue 28/01/14**	**138**	**CC**
34	100%	Install ROS	5 days	Tue 07/01/14	Mon 13/01/14		CC
35	100%	Implement Mapping	1 day?	Tue 21/01/14	Tue 21/01/14	144	CC
36	100%	Check Systems & wait for user	5 days	Wed 22/01/14	Tue 28/01/14	145	CC
37	**100%**	**Arm Program (Raspberry Pi)**	**23 days**	**Tue 07/01/14**	**Thu 06/02/14**	**137**	**CC**
38	100%	Connect to Sensors & Read Data	5 days	Tue 07/01/14	Mon 13/01/14		CC
39	100%	Send & Receive "Heartbeat" over Network	3 days	Tue 14/01/14	Thu 16/01/14	148	CC
40	100%	Send & Receive Control & Sensor Data over Network	2 days	Fri 17/01/14	Mon 20/01/14	149	CC
41	100%	Implement Control on Arm (Inverse Kinematics?)	10 days	Tue 21/01/14	Mon 03/02/14	150	CC
42	100%	Stream Webcam Images	3 days	Tue 04/02/14	Thu 06/02/14	151	CC
43	**100%**	**Competition Tasks**	**125 days**	**Tue 15/10/13**	**Mon 07/04/14**		
44	**100%**	**Competition Deadlines**	**89.13 days**	**Tue 15/10/13**	**Mon 17/02/14**		
45	100%	Competition Registration	2 hrs	Tue 15/10/13	Tue 15/10/13		CC
46	100%	Team Member Names Due	1 hr	Mon 16/12/13	Mon 16/12/13	155	CC
47	100%	Team Fee Due	1 hr	Mon 17/02/14	Mon 17/02/14	156	VD
48	100%	Setup Days	2 days	Tue 01/04/14	Wed 02/04/14	157	AP,CC,J
49	100%	Competition Days	3 days	Thu 03/04/14	Mon 07/04/14	157	AP,CC,J
50	**98%**	**Academic Deadlines**	**144 days**	**Tue 22/10/13**	**Fri 09/05/14**		
51	**100%**	**Deadline Preparation**	**132 days**	**Thu 17/10/13**	**Fri 18/04/14**		
52	100%	**1st Report Preparation**	4 days	Thu 17/10/13	Tue 22/10/13		CC
53	**100%**	**2nd Report Preparation**	**4.3 days**	**Tue 26/11/13**	**Mon 02/12/13**		
54	100%	Document Structure	0.2 days	Tue 26/11/13	Tue 26/11/13		CC



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ed 23/04/14

Task | Summary | Inactive Milestone | Duration-only | Start-only | External Milestone | Manual Progress
Split | Project Summary | Inactive Summary | Manual Summary Rollup | Finish-only | Deadline
Milestone | Inactive Task | Manual Task | Manual Summary | External Tasks | Progress

Appendix C – Sponsor Contributions

Table 7 discusses the details of the sponsorship partnerships gained this year.

Table 7: Details of Sponsorship Partners

School of Engineering	The School of Engineering and Warwick Manufacturing Group combined provided the project with £5,000.
WMG Innovative Solutions	
CATAPULT High Value Manufacturing	WMG Centre HVM Catapult provided the team with £2,500 to go towards the new robot.
MOUSER ELECTRONICS	Mouser Electronics offered the team electronics amounting to £440.
MakerBeam	MakerBeam provided £356 worth of beams, brackets, nuts and bolts for the chassis and arm.
HARWiN	Harwin assisted the team by providing all of the electrical connectors for the new robot.
warwick SU	Warwick SU Projects Fund agreed to provide £750 towards competition costs.
GTSS	GTSS supplied the team with a whole new set of tools amounting to £650.
AUTODESK	Autodesk gave WMR access to a free 2014 license for AutoCAD Inventor.
The Vice Chancellor The University of Warwick	The Vice Chancellor and Registrar's Office gave the team £1000 towards competition costs.

Appendix D – Mass and Cost Distribution Analysis

Assembly	Sub-Assembly	Categories	Component	Qty.	Material	Mass (kg)	% Robot	Cost (£)	% Robot
Chassis	Chassis	Mounting Plates	Tufnol Base	1	Tufnol	0.104	0.42%	10.00	0.27%
Chassis	Chassis	Mounting Plates	Tufnol Middle Rear	1	Tufnol	0.112	0.45%	17.50	0.47%
Chassis	Chassis	Mounting Plates	Tufnol Middle Front	1	Tufnol	0.128	0.52%	17.50	0.47%
Chassis	Chassis	Mounting Plates	Arm Chassis Mount	1	Aluminium 6083-T5	0.051	0.21%	3.80	0.10%
Chassis	Chassis	Mounting Plates	Axle Mounting Plate 1	2	Aluminium 6083-T5	0.184	0.74%	10.00	0.27%
Chassis	Chassis	Mounting Plates	Axle Mounting Plate 2	2	Aluminium 6083-T5	0.184	0.74%	6.00	0.16%
Chassis	Chassis	Mounting Plates	Encoder Mounting Plate	2	Aluminium 6063-T6	0.014	0.06%	22.48	0.60%
Chassis	Chassis	Shell	Bottom Plate	1	Aluminium 6083-T5	0.298	1.20%	0.00	0.00%
Chassis	Chassis	Mounting Plates	Motor Mounting Plate	4	Aluminium 6083-T5	0.228	0.92%	8.00	0.21%
Chassis	Chassis	Mounting Plates	Emergency Stop Plate	1	Aluminium 6083-T5	0.026	0.10%	3.50	0.09%
Chassis	Chassis	Mounting Plates	Battery Housing	1	ABS	0.051	0.21%	2.04	0.05%
Chassis	Chassis	Mounting Plates	Arm Control Box	1	ABS	0.115	0.46%	4.60	0.12%
Chassis	Chassis	Shell	Shell Top Plate	1	Polycarbonate	0.115	0.46%	4.00	0.11%
Chassis	Chassis	Shell	Shell Side Plate	2	Polycarbonate	0.246	0.99%	8.00	0.21%
Chassis	Chassis	Shell	Shell Front Plate	1	Polycarbonate	0.044	0.18%	7.50	0.20%
Chassis	Chassis	Shell	Shell Back Plate	1	Polycarbonate	0.045	0.18%	3.00	0.08%
Chassis	Chassis	MakerBeam	Makerbeam 430mm	8	Aluminium 6063-T5	0.447	1.80%	25.88	0.69%
Chassis	Chassis	MakerBeam	Makerbeam 140mm	10	Aluminium 6063-T5	0.182	0.73%	10.53	0.28%
Chassis	Chassis	MakerBeam	Makerbeam 65mm	2	Aluminium 6063-T5	0.017	0.07%	0.98	0.03%
Chassis	Chassis	MakerBeam	Makerbeam 66mm	6	Aluminium 6063-T5	0.051	0.21%	2.98	0.08%
Chassis	Chassis	MakerBeam	Makerbeam 59mm	4	Aluminium 6063-T5	0.031	0.12%	1.78	0.05%
Chassis	Chassis	MakerBeam	Makerbeam 155mm	4	Aluminium 6063-T5	0.081	0.32%	4.66	0.12%
Chassis	Chassis	MakerBeam	90 Degree Brackets	6	Stainless Steel	0.024	0.10%	63.34	1.69%
Chassis	Chassis	MakerBeam	Corner Brackets	45	Stainless Steel	0.315	1.27%	49.76	1.33%
Chassis	Chassis	MakerBeam	Angle Bracket	4	Stainless Steel	0.020	0.08%	9.05	0.24%
Chassis	Chassis	MakerBeam	M3 Square Head 12mm Bolts	71	Stainless Steel	0.036	0.14%	22.68	0.61%
Chassis	Chassis	MakerBeam	M3 Square Head 6mm Bolts	261	Stainless Steel	0.112	0.45%	54.25	1.45%
Chassis	Chassis	Fixings	M3 Bolts	22	Stainless Steel	0.017	0.07%	7.15	0.19%
Chassis	Chassis	Fixings	M3 Nuts	243	Stainless Steel	0.075	0.30%	8.80	0.24%
Chassis	Chassis	Fixings	M3 Nyloc Nuts	40	Stainless Steel/ Nylon	0.019	0.08%	3.76	0.10%
Chassis	Chassis	Fixings	Nylon Spacers	4	Nylon	0.001	0.00%	8.80	0.24%
Chassis	Chassis	Electronics	Pico ITX board	1	n/a	0.300	1.21%	278.51	7.44%

Chassis	Chassis	Electronics	Hard drive	1	n/a	0.092	0.37%	43.38	1.16%
Chassis	Chassis	Electronics	Raspberry Pi camera (with mount)	1	n/a	0.006	0.02%	16.56	0.44%
Chassis	Chassis	Electronics	Raspberry Pi (camera)	1	n/a	0.045	0.18%	27.48	0.73%
Chassis	Chassis	Electronics	Router	1	n/a	0.401	1.61%	162.61	4.35%
Chassis	Chassis	Electronics	PCB	1	n/a	0.200	0.81%	42.00	1.12%
Chassis	Chassis	Electronics	Emergency stop button	1	n/a	0.041	0.17%	0.00	0.00%
Chassis	Chassis	Electronics	Relay	1	n/a	0.133	0.54%	7.54	0.20%
Chassis	Chassis	Electronics	Relay (arm)	1	n/a	0.056	0.23%	102.12	2.73%
Chassis	Chassis	Electronics	Battery	1	n/a	0.754	3.04%	0.00	0.00%
Chassis	Chassis	Electronics	LIDAR	1	n/a	0.146	0.59%	17.09	0.46%
Chassis	Chassis	Electronics	Speaker (with mount)	1	n/a	0.010	0.04%	5.32	0.14%
					Total System:	**5.557**	**22.37%**	**£ 1,104.93**	**29.53%**
Assembly	Sub-Assembly	Categories	Component	Qty.	Material	Mass (kg)	% Robot	Cost (£)	% Robot
Drivetrain	Track units	Electronics	Motor	4	n/a	1.800	7.25%	121.60	3.25%
Drivetrain	Track units	Manufactured	Side Panel	8	Aluminium	1.744	7.02%	115.60	3.09%
Drivetrain	Track units	Manufactured	Motor Spacing Plate	4	Aluminium	0.072	0.29%	24.00	0.64%
Drivetrain	Track units	Manufactured	Cross Bracer	12	Aluminium	0.072	0.29%	101.40	2.71%
Drivetrain	Track units	Manufactured	Mounting Bar	8	Aluminium	0.136	0.55%	121.60	3.25%
Drivetrain	Track units	Electronics	SyRen 25	4	n/a	0.224	0.90%	238.56	6.38%
Drivetrain	Track units	Manufactured	Worm Support Base	4	Aluminium	0.072	0.29%	0.00	0.00%
Drivetrain	Track units	Manufactured	Coupling	4	Aluminium	0.060	0.24%	57.80	1.54%
Drivetrain	Track units	Manufactured	Coupling Axle	4	Silver Steel	0.104	0.42%	0.00	0.00%
Drivetrain	Track units	Off-the-shelf mechanical	Worm Gear	4	Steel	0.208	0.84%	0.00	0.00%
Drivetrain	Track units	Manufactured	Axle Front	4	Silver Steel	0.152	0.61%	121.20	3.24%
Drivetrain	Track units	Off-the-shelf mechanical	Wheel Gear	4	Phosphor Bronze	0.084	0.34%	0.00	0.00%
Drivetrain	Track units	Off-the-shelf mechanical	Sprocket Front	8	Mild Steel	1.416	5.70%	108.18	2.89%
Drivetrain	Track units	Off-the-shelf mechanical	Sprocket Bush Front	8	n/a	0.032	0.13%	260.20	6.95%
Drivetrain	Track units	Off-the-shelf mechanical	Worm Bush	4	n/a	0.004	0.02%	102.52	2.74%
Drivetrain	Track units	Manufactured	Worm Support	4	Aluminium	0.056	0.23%	167.64	4.48%
Drivetrain	Track units	Manufactured	Worm Support Rod	12	Aluminium	0.120	0.48%	0.00	0.00%
Drivetrain	Track units	Manufactured	Flipper Axle Hat	4	Aluminium	0.180	0.72%	12.00	0.32%
Drivetrain	Track units	Off-the-shelf mechanical	Sprocket Back	8	Mild Steel	2.168	8.73%	0.00	0.00%
Drivetrain	Track units	Off-the-shelf mechanical	Sprocket Bush Back	8	n/a	0.008	0.03%	0.00	0.00%
Drivetrain	Track units	Manufactured	Tensioning Block	4	Acetal Resin	0.800	3.22%	60.00	1.60%
Drivetrain	Track units	Treads	Chain	8	Steel	0.848	3.41%	460.48	12.31%

Drivetrain	Track units	Treads	U channel	4	Aluminium	1.568	6.31%	114.16	3.05%
Drivetrain	Track units	Treads	Tube	4	Rubber	1.344	5.41%	65.00	1.74%
Drivetrain	Track units	Treads	Track fastenings	4	Steel	0.336	1.35%	0.00	0.00%
Drivetrain	Track units	Off-the-shelf mechanical	M5 Bolt	26	Stainless Steel	0.078	0.31%	2.08	0.06%
Drivetrain	Flipper system	Electronics	Motor	2	n/a	0.900	3.62%	4.00	0.11%
Drivetrain	Flipper system	Off-the-shelf mechanical	Worm Gear	2	Steel	0.278	1.12%	4.00	0.11%
Drivetrain	Flipper system	Off-the-shelf mechanical	Wheel Gear	2	Phosphor Bronze	0.692	2.79%	0.00	0.00%
Drivetrain	Flipper system	Manufactured	Motor Axle Extension	2	Silver Steel	0.188	0.76%	4.00	0.11%
Drivetrain	Flipper system	Off-the-shelf mechanical	Spur Gear Axle	2	Delrin	0.014	0.06%	96.48	2.58%
Drivetrain	Flipper system	Off-the-shelf mechanical	Spur Gear Encoder	2	Delrin	0.022	0.09%	43.26	1.16%
Drivetrain	Flipper system	Manufactured	Flipper Axle	2	Silver Steel	0.916	3.69%	12.94	0.35%
Drivetrain	Flipper system	Electronics	Encoder	2	n/a	0.026	0.10%	12.94	0.35%
Drivetrain	Flipper system	Off-the-shelf mechanical	Bearing	6	n/a	0.198	0.80%	37.68	1.01%
Drivetrain	Flipper system	Electronics	Motor control board (flippers)	1	n/a	0.090	0.36%	26.68	0.71%
					Total System:	**17.010**	**68.49%**	**£1973.44**	**52.74%**
Assembly	Sub-Assembly	Categories	Component	Qty.	Material	Mass (kg)	% Robot	Cost (£)	% Robot
Arm System	Joint 1	MakerBeam	MakerBeam - 35mm	2	Aluminium 6082 T6	0.009	0.04%	0.53	0.01%
Arm System	Joint 1	MakerBeam	MakerBeam - 55mm	2	Aluminium 6082 T6	0.015	0.06%	0.83	0.02%
Arm System	Joint 1	MakerBeam	MakerBeam - 62mm	4	Aluminium 6082 T6	0.033	0.13%	1.87	0.05%
Arm System	Joint 1	Other manufactured components	Side Reinforcement	2	Aluminium 6082 T6	0.022	0.09%	0.28	0.01%
Arm System	Joint 1	Other manufactured components	Base Reinforcement	2	Aluminium 6082 T6	0.009	0.03%	0.05	0.00%
Arm System	Joint 1	Motor	RC Servo	1	n/a	0.060	0.24%	19.68	0.53%
Arm System	Joint 1	Other manufactured components	Servo Motor Bracket	1	Aluminium 6082 T6	0.006	0.03%	0.12	0.00%
Arm System	Joint 1	Transmission	Attachment	1	n/a	0.001	0.00%	0.00	0.00%
Arm System	Joint 1	Transmission	Sprocket metal	2	Mild Steel	0.040	0.16%	14.90	0.40%
Arm System	Joint 1	Transmission	Sprocket plastic	0	Derlin	0.000	0.00%	0.00	0.00%
Arm System	Joint 1	Transmission	Chain metal	1	Mild Steel	0.018	0.07%	4.92	0.13%
Arm System	Joint 1	Transmission	Chain plastic	0	Derlin	0.000	0.00%	0.00	0.00%
Arm System	Joint 1	Transmission	Axle 55mm	1	Aluminium 6082 T6	0.007	0.03%	0.26	0.01%
Arm System	Joint 1	Transmission	Worm Metal	1	Unharded Mild Steel	0.024	0.10%	18.17	0.49%
Arm System	Joint 1	Transmission	Worm Plastic	0	Derlin	0.000	0.00%	0.00	0.00%
Arm System	Joint 1	Other manufactured components	Worm Support 5mm	2	Aluminium 5083 T6	0.021	0.09%	0.59	0.02%
Arm System	Joint 1	Other manufactured components	Worm Support 3mm	0	Aluminium 6082 T6	0.000	0.00%	0.00	0.00%
Arm System	Joint 1	Transmission	IGUS bearing - hat	2	Unknown	0.001	0.00%	1.72	0.05%
Arm System	Joint 1	Other manufactured components	Tufnol Slider	2	Carp Brand Tufnol	0.014	0.06%	3.50	0.09%

Arm System	Joint 1	Transmission	Axle 47mm	1	Aluminium 6082 T6	0.006	0.03%	0.26	0.01%
Arm System	Joint 1	Arm Electronics	Encoder	1	n/a	0.016	0.06%	25.43	0.68%
Arm System	Joint 1	Transmission	Worm Gear plastic	1	Derlin	0.016	0.06%	13.39	0.36%
Arm System	Joint 1	Other manufactured components	Mesh Adjuster	2	Aluminium 6082 T6	0.011	0.04%	0.26	0.01%
Arm System	Joint 1	Transmission	IGUS bearing - flat	2	Unknown	0.000	0.00%	1.62	0.04%
Arm System	Joint 1	Fixings	M3 bolt-6mm (8mm total) & Nut	38	Steel	0.027	0.11%	2.98	0.08%
Arm System	Joint 1	Other manufactured components	Upper Joint	2	Aluminium 6082 T6	0.016	0.06%	0.19	0.01%
Arm System	Joint 1	MakerBeam	MakerBeam - 35mm	2	Aluminium 6082 T6	0.009	0.04%	0.53	0.01%
Arm System	Joint 1	MakerBeam	MakerBeam - 62mm	2	Aluminium 6082 T6	0.017	0.07%	0.93	0.02%
Arm System	Joint 1	Fixings	Corner bracket (mod L)	4	Mild Steel	0.012	0.05%	2.60	0.07%
Arm System	Link 1	Other manufactured components	Wrist connector	1	Aluminium 5083 T6	0.011	0.04%	0.14	0.00%
Arm System	Link 1	Other manufactured components	Socket	1	ABS	0.003	0.01%	0.00	0.00%
Arm System	Link 1	Other manufactured components	Ball	1	ABS	0.003	0.01%	0.00	0.00%
Arm System	Link 1	Fixings	Lower ball and socket fixing	1	Mild Steel	0.004	0.02%	0.73	0.02%
Arm System	Link 1	Fixings	Upper ball and socket fixing	1	Mild Steel	0.003	0.01%	0.65	0.02%
Arm System	Link 1	Cable System	35mm M3 nut and bolt	4	Mild Steel	0.010	0.04%	0.31	0.01%
Arm System	Link 1	Cable System	Cable termination upper	4	Mild Steel	0.012	0.05%	11.44	0.31%
Arm System	Link 1	Cable System	Cable termination Lower	4	Mild Steel	0.019	0.08%	5.20	0.14%
Arm System	Link 1	Fixings	M3 bolt-6mm (8mm total)& Nut	6	Mild Steel	0.004	0.02%	0.47	0.01%
Arm System	Link 1	MakerBeam	Open Beam	1	Aluminium 5083 T6	0.099	0.40%	3.23	0.09%
Arm System	Link 1	Cable System	Cable 250mm	4	Steel	0.009	0.04%	0.88	0.02%
Arm System	Link 1	Other manufactured components	Base Reinforcement	1	Aluminium 5083 T6	0.004	0.02%	0.03	0.00%
Arm System	Link 1	Other manufactured components	Elbow T Bracket	2	Aluminium 5083 T6	0.015	0.06%	0.24	0.01%
Arm System	Link 1	Cable System	Top end cable termination	2	Mild Steel	0.032	0.13%	6.56	0.18%
Arm System	Link 1	Cable System	Cable termination upper	2	Mild Steel	0.006	0.02%	5.72	0.15%
Arm System	Link 1	Cable System	Cable termination lower	2	Mild Steel	0.009	0.04%	2.60	0.07%
Arm System	Link 1	Cable System	Cable 35mm	2	Steel	0.001	0.00%	0.07	0.00%
Arm System	Joint 2	MakerBeam	MakerBeam - 35mm	2	Aluminium 6082 T6	0.009	0.04%	0.53	0.01%
Arm System	Joint 2	MakerBeam	MakerBeam - 55mm	2	Aluminium 6082 T6	0.015	0.06%	0.83	0.02%
Arm System	Joint 2	MakerBeam	MakerBeam - 62mm	4	Aluminium 6082 T6	0.033	0.13%	1.87	0.05%
Arm System	Joint 2	Other manufactured components	Side Reinforcement	2	Aluminium 6082 T6	0.022	0.09%	0.28	0.01%
Arm System	Joint 2	Other manufactured components	Base Reinforcement	2	Aluminium 6082 T6	0.009	0.03%	0.05	0.00%
Arm System	Joint 2	Motor	RC Servo	1	n/a	0.060	0.24%	19.68	0.53%
Arm System	Joint 2	Other manufactured components	Servo Motor Bracket	1	Aluminium 6082 T6	0.006	0.03%	0.12	0.00%
Arm System	Joint 2	Transmission	Attachment	1	n/a	0.001	0.00%	0.00	0.00%

Arm System	Joint 2	Transmission	Sprocket metal	2	Mild Steel	0.040	0.16%	14.90	0.40%
Arm System	Joint 2	Transmission	Sprocket plastic	0	Derlin	0.000	0.00%	0.00	0.00%
Arm System	Joint 2	Transmission	Chain Metal	1	Mild Steel	0.018	0.07%	4.92	0.13%
Arm System	Joint 2	Transmission	Chain plastic	0	Derlin	0.000	0.00%	0.00	0.00%
Arm System	Joint 2	Transmission	Axle 55mm	1	Aluminium 6082 T6	0.007	0.03%	0.26	0.01%
Arm System	Joint 2	Transmission	Worm Metal	1	Unharded Mild Steel	0.024	0.10%	18.17	0.49%
Arm System	Joint 2	Transmission	Worm Plastic	0	Derlin	0.000	0.00%	0.00	0.00%
Arm System	Joint 2	Other manufactured components	Worm Support 5mm	2	Aluminium 5083 T6	0.021	0.09%	0.58	0.02%
Arm System	Joint 2	Other manufactured components	Worm Support 3mm	0	Aluminium 6082 T6	0.000	0.00%	0.00	0.00%
Arm System	Joint 2	Transmission	IGUS bearing - Hat	2	Unknown	0.001	0.00%	1.72	0.05%
Arm System	Joint 2	Other manufactured components	Tufnol Slider	2	Carp Brand Tufnol	0.014	0.06%	3.50	0.09%
Arm System	Joint 2	Transmission	Axle 47mm	1	Aluminium 6082 T6	0.006	0.03%	0.26	0.01%
Arm System	Joint 2	Arm Electronics	Encoder	1	n/a	0.016	0.06%	25.43	0.68%
Arm System	Joint 2	Transmission	Worm Gear plastic	1	Derlin	0.016	0.06%	13.39	0.36%
Arm System	Joint 2	Other manufactured components	Mesh Adjuster	2	Aluminium 6082 T6	0.011	0.04%	0.26	0.01%
Arm System	Joint 2	Transmission	IGUS bearing - flat	2	Unknown	0.000	0.00%	1.62	0.04%
Arm System	Joint 2	Fixings	M3 bolt-6mm (8mm total) & Nut	56	Steel	0.039	0.16%	4.48	0.12%
Arm System	Joint 2	Other manufactured components	Upper Joint	2	Aluminium 6082 T6	0.016	0.06%	0.19	0.01%
Arm System	Joint 2	MakerBeam	MakerBeam - 35mm	2	Aluminium 6082 T6	0.009	0.04%	0.53	0.01%
Arm System	Joint 2	MakerBeam	MakerBeam - 62mm	2	Aluminium 6082 T6	0.017	0.07%	1.62	0.04%
Arm System	Joint 2	Fixings	Corner bracket (mod L)	4	Mild Steel	0.012	0.05%	2.60	0.07%
Arm System	Link 2	Other manufactured components	Wrist connector	1	Aluminium 5083 T6	0.011	0.04%	0.14	0.00%
Arm System	Link 2	Other manufactured components	Socket	1	ABS	0.003	0.01%	0.00	0.00%
Arm System	Link 2	Other manufactured components	Ball	1	ABS	0.003	0.01%	0.00	0.00%
Arm System	Link 2	Cable System	Cable termination upper	4	Mild Steel	0.012	0.05%	0.00	0.00%
Arm System	Link 2	Cable System	Cable termination lower	4	Mild Steel	0.019	0.08%	2.92	0.08%
Arm System	Link 2	Fixings	Lower ball and socket fixing	1	Mild Steel	0.004	0.02%	0.73	0.02%
Arm System	Link 2	Fixings	Upper ball and socket fixing	1	Mild Steel	0.003	0.01%	0.65	0.02%
Arm System	Link 2	Fixings	35mm M3 nut and bolt	4	Mild Steel	0.010	0.04%	0.30	0.01%
Arm System	Link 2	MakerBeam	Open Beam	1	Aluminium 6082 T6	0.099	0.40%	3.23	0.09%
Arm System	Link 2	Cable System	Cable 250mm	4	Steel	0.009	0.04%	0.88	0.02%
Arm System	Link 2	Cable System	Top end cable termination	2	Mild Steel	0.032	0.13%	6.56	0.18%
Arm System	Link 2	Fixings	M3 bolt-6mm (8mm total) & Nut	14	Mild Steel	0.010	0.04%	1.12	0.03%
Arm System	Link 2	Cable System	Cable termination upper	2	Mild Steel	0.006	0.02%	0.44	0.01%
Arm System	Link 2	Cable System	Cable termination lower	2	Mild Steel	0.009	0.04%	0.05	0.00%

Arm System	Link 2	Cable System	Cable 35mm	2	Steel	0.001	0.00%	0.07	0.00%
Arm System	Link 2	Other manufactured components	Wrist connector	1	Aluminium 5083 T6	0.011	0.04%	0.14	0.00%
Arm System	Link 2	MakerBeam	MakerBeam - 35mm	1	Aluminium 6082 T6	0.005	0.02%	0.26	0.01%
Arm System	Link 2	Fixings	Corner bracket (mod L)	4	Mild Steel	0.012	0.05%	2.60	0.07%
Arm System	Joint 3	MakerBeam	MakerBeam - 35mm	2	Aluminium 6082 T6	0.009	0.04%	0.53	0.01%
Arm System	Joint 3	MakerBeam	MakerBeam - 55mm	2	Aluminium 6082 T6	0.015	0.06%	0.83	0.02%
Arm System	Joint 3	MakerBeam	MakerBeam - 62mm	4	Aluminium 6082 T6	0.033	0.13%	1.87	0.05%
Arm System	Joint 3	Other manufactured components	Side Reinforcement	2	Aluminium 6082 T6	0.022	0.09%	0.28	0.01%
Arm System	Joint 3	Other manufactured components	Base Reinforcement	2	Aluminium 6082 T6	0.009	0.03%	0.05	0.00%
Arm System	Joint 3	Motor	RC Servo	1	n/a	0.060	0.24%	19.68	0.53%
Arm System	Joint 3	Other manufactured components	Servo Motor Bracket	1	Aluminium 6082 T6	0.006	0.03%	0.12	0.00%
Arm System	Joint 3	Transmission	Attachment	1	n/a	0.001	0.00%	0.00	0.00%
Arm System	Joint 3	Transmission	Sprocket metal	0	Mild Steel	0.000	0.00%	0.00	0.00%
Arm System	Joint 3	Transmission	Sprocket plastic	2	Derlin	0.006	0.02%	9.52	0.25%
Arm System	Joint 3	Transmission	Chain Metal	0	Mild Steel	0.000	0.00%	0.00	0.00%
Arm System	Joint 3	Transmission	Chain plastic	1	Derlin	0.006	0.02%	7.64	0.20%
Arm System	Joint 3	Transmission	Axle 55mm	1	Aluminium 6082 T6	0.007	0.03%	0.26	0.01%
Arm System	Joint 3	Transmission	Worm Metal	0	Unharded Mild Steel	0.000	0.00%	0.00	0.00%
Arm System	Joint 3	Transmission	Worm Plastic	1	Derlin	0.004	0.02%	9.99	0.27%
Arm System	Joint 3	Other manufactured components	Worm Support 5mm	0	Aluminium 5083 T6	0.000	0.00%	0.00	0.00%
Arm System	Joint 3	Other manufactured components	Worm Support 3mm	2	Aluminium 6082 T6	0.013	0.05%	0.16	0.00%
Arm System	Joint 3	Transmission	IGUS bearing - Hat	2	Unknown	0.001	0.00%	1.72	0.05%
Arm System	Joint 3	Other manufactured components	Tufnol Slider	2	Carp Brand Tufnol	0.014	0.06%	3.50	0.09%
Arm System	Joint 3	Transmission	Axle 47mm	1	Aluminium 6082 T6	0.006	0.03%	0.26	0.01%
Arm System	Joint 3	Arm Electronics	Encoder	1	n/a	0.016	0.06%	25.43	0.68%
Arm System	Joint 3	Transmission	Worm Gear plastic	1	Derlin	0.016	0.06%	13.39	0.36%
Arm System	Joint 3	Other manufactured components	Mesh Adjuster	2	Aluminium 6082 T6	0.011	0.04%	0.26	0.01%
Arm System	Joint 3	Transmission	IGUS bearing - flat	2	Unknown	0.000	0.00%	1.62	0.04%
Arm System	Joint 3	Fixings	M3 bolt-6mm (8mm total)& Nut	44	Steel	0.031	0.12%	3.52	0.09%
Arm System	Joint 3	Other manufactured components	Upper Joint	2	Aluminium 6082 T6	0.016	0.06%	0.19	0.01%
Arm System	Joint 4	Other manufactured components	Servo Holder	1	Aluminium 6082 T6	0.011	0.04%	6.48	0.17%
Arm System	Joint 4	Motor	RC Servo	1	n/a	0.060	0.24%	19.68	0.53%
Arm System	Joint 4	MakerBeam	MakerBeam - 35mm	1	Aluminium 6082 T6	0.005	0.02%	0.26	0.01%
Arm System	Joint 4	Transmission	Attachment	1	n/a	0.001	0.00%	0.00	0.00%
Arm System	Joint 4	Fixings	M3 bolt-6mm (8mm total)& Nut	7	Mild Steel	0.005	0.02%	0.56	0.01%

Arm System	Electronics	Arm Electronics	Raspberry Pi (arm)	1	n/a	0.045	0.18%	27.48	0.73%
Arm System	Electronics	Arm Electronics	Servo motor controller (arm)	1	n/a	0.026	0.10%	86.83	2.32%
Arm System	Electronics	Arm Electronics	PCB (arm)	1	n/a	0.185	0.74%	32.00	0.86%
Arm System	Head	Other manufactured components	Main Plate	1	Aluminium 6082 T6	0.042	0.17%	1.43	0.04%
Arm System	Head	Other manufactured components	Camera Enclosures	2	ABS	0.022	0.09%	2.82	0.08%
Arm System	Head	Arm Electronics	Webcam	2	n/a	0.012	0.05%	35.96	0.96%
Arm System	Head	Arm Electronics	CO2 Sensor	1	n/a	0.027	0.11%	34.97	0.93%
Arm System	Head	Fixings	Enclosure Case Screws	4	Stainless Steel	0.002	0.01%	0.00	0.00%
Arm System	Head	Fixings	M5 Bolts	4	Stainless Steel	0.012	0.05%	0.32	0.01%
Arm System	Gripper	Gripper	Main Gripper with Mounts	1	Aluminium	0.090	0.36%	9.95	0.27%
Arm System	Gripper	Gripper	Pinion Gear	1	n/a	0.008	0.03%	0.00	0.00%
Arm System	Gripper	Gripper	Clutch	1	n/a	0.027	0.11%	0.00	0.00%
Arm System	Gripper	Gripper	Fastener for Clutch and Gear	1	Stainless Steel	0.003	0.01%	0.00	0.00%
Arm System	Gripper	Motor	Medium Servo	1	n/a	0.021	0.08%	8.95	0.24%
Arm System	Gripper	Fixings	Servo Fastener	1	Stainless Steel	0.008	0.03%	0.00	0.00%
Arm System	Gripper	Fixings	M3 Bolts	12	Stainless Steel	0.009	0.04%	0.48	0.01%
Arm System	Gripper	Fixings	M3 Nut	12	Stainless Steel	0.004	0.01%	0.36	0.01%
Arm System	Gripper	Gripper	New Fingers	4	Aluminium 6082 T6	0.017	0.07%	2.00	0.05%
					Total System:	**2.269**	**9.14%**	**£663.11**	**17.72%**
					Total Mass (kg):	**24.836**	**Cost (£):**	**£3,741.48**	