

# **RoboCupRescue 2013 - Robot League Team Warwick Mobile Robotics (UK)**

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**Abstract.** Warwick Mobile Robotics is developing a highly mobile urban search and rescue robot. Having finished second in the 2012 German Open and attained Best in Class Mobility and Best in Class Manipulation, the team is now aiming to progress to the World RoboCup. Design efforts this year have been focused on improved reliability and more intuitive controls. Reliability has been achieved by redesigning robot chassis and its power system. The re-engineered chassis along with a new battery system have been designed with ease of maintenance in mind. The highly improved Graphical User Interface (GUI) has made the system simpler to use and implementation of inverse kinematics has achieved easier arm control. These enhancements support our ultimate goal of deploying the robot in real-life disaster situations.

## **Introduction**

Warwick Mobile Robotics (WMR) is a Masters level undergraduate project at the University of Warwick, which has been on-going over the last five years. Each year a new team arrives as they enter their final Masters course, and develops and improves the existing tele-operated robot.

This successful and innovative team has chosen to enter the German Open RoboCup competition for the last four years. Last year WMR were placed second overall and retained the Best in Mobility award (an achievement held since 2009). The team was also named the Best in Manipulation. Having continuously excelled at the German Open competition and attaining first place in 2010, WMR is looking to progress to the World competition for 2013.

The Aims for 2013 are as follows:

- To aid the continuing development of the existing robot's systems, with particular focus on delivering reliability and commercial viability
- To qualify for and enter the RoboCup Rescue World Championship
- To develop a lighter and stronger chassis that allows for better serviceability
- To improve the robustness of the robot
- To upgrade the existing software to enable improved human-robot interaction

With a greatly improved robot, this year's team wishes to represent the UK at the 2013 World RoboCup Rescue competition in Eindhoven.

## 1. Team Members and Their Contributions

The team comprises of six multi-disciplinary Masters students from the University of Warwick School of Engineering. The members are recognised below, along with their technical contributions.

- Edgar Zauls – Manufacturing and mechanical design
- Lewis Judd – Mechanical design
- Michael Tayler-Grint – Power electronics development
- Nick Orłowski – Head electronics design
- Kristian Buckstone – Software development
- Rachele Williams – System modelling

Eight institutions, whose support varies from monetary to technical partnerships, sponsor Warwick Mobile Robotics.

- WMG [12.] – a department at the University of Warwick which promotes technical innovation. The sponsor provides monetary support, technical assistance and a team office.
- WMG centre HVM Catapult [11.] – a consortium of seven UK research centres, one of which is within WMG. Catapult's focus is on Low Carbon Mobility. The sponsor provides monetary assistance to the development and research into lightweight material usage and energy storage and management.
- Northrop Grumman [6.] – Remotec, as part of Northrop Grumman Corporation, have formed a partnership with the WMR team to share technical expertise and provide testing facilities.
- Harwin [2.] – manufacturers of highly reliable interconnect devices provide the team with technical support and an allowance of their products.
- Mouser Electronics [5.] – an online semiconductor and electronic component distributor provides the team with an allowance of their products.
- Maxon Motor [4.] – the leading provider of high-precision drive systems up to 500 W have supported WMR by permitting purchase of their products at cost price.
- University of Warwick Office of the Vice Chancellor [8.] – A long-standing sponsor of the project who has chosen to continue monetary support this year to help with travel costs.

- School of Engineering [9.]- one of the leading unified engineering schools in the UK in which the team has studied over four years, and will acquire their Masters from here.

## 2. Operator Station Set-up and Break-Down (10 minutes)



**Fig. 1.** Operator station being used to control the WMR robot.

The current operator station is a laptop with an external Wi-Fi antenna and PlayStation 3 controller (a headset for communication is also optional depending on the environment). As a laptop is used, there is no direct need for external monitors but they can be attached if desired and the user interface automatically resizes itself for any screen size. The flexible software can be run on any laptop or newer tablet PCs meaning that the system is highly portable. Whilst the current laptop is not significantly protected against the environment, it is light, has substantial battery power and could easily be taken up a ladder in a backpack and used outdoors.

In a real disaster scenario the operator would have a rugged laptop with the peripherals attached and stored within the case. A table and chair could be used however the operator can use the system by just resting the laptop on their lap, in which case only a stool at most would be required.

The start-up procedure consists of a number of simple stages:

1. Plug in and boot up the laptop (30 seconds)
2. Plug in the batteries and switch on the robot (30 seconds)
3. Establish a wireless connection with the robot from the laptop (30 seconds)
4. Log in to the robot remotely from the laptop (30 seconds)
5. Run the robot interface software and enable the controller (30 seconds).

As there are just a few simple steps, this task can be managed in approximately two and a half minutes by one operator. A lot of effort has been made to make this process

as simple as possible so that someone without prior knowledge of the system can use it. The process would be quicker without the need to type in passwords but for the sake of security they are included in the log in procedure.

The shutdown procedure is much simpler and can be performed by simply clicking a button on the interface which shuts down the computer inside the robot. The batteries are then removed from the robot, and the laptop is powered down. This process takes approximately one minute.

The robot itself has undergone a process of light-weighting which makes it much more portable. With a weight of approximately 35kg, two people can easily carry the robot however currently it is manoeuvred with the use of skates. Ideally in the future, a case will be developed which stores the robot and has its own wheels and handle. At the moment, the robot as it is not overly large and can easily fit into a medium-sized box with the arm in the down position, so portability is not a major issue.

### 3. Communications

The robot is controlled by Wi-Fi radio communications, primarily using 802.11A channels although it is capable of using 802.11B/G channels too. The robot contains an Asus RT-N56U router, which creates a network when the robot is powered on. The base station laptop connects to this network and starts the robot's main program via SSH. The main program creates a server run on the robot's CPU which the base station laptop can connect to as a client. Commands and data are then sent in both directions using this link.

To avoid unsafe operation during loss of radio communications, the robot is programmed to monitor the data stream from the base station – in the event that communications are interrupted, the robot will stop moving and attempt to re-establish contact. Further autonomy such as returning to a previously occupied area of good reception in the event of radio drop-out is planned but not yet implemented.

Due to the configuration of the robot's communication system it should be possible to use an active tether connection over a standard Ethernet cable. This would require a suitable method for laying and retrieving the cable so this feature is not being implemented this year.

<b>Rescue Robot League</b>		
<b>Warwick Mobile Robotics (United Kingdom)</b>		
MODIFY TABLE TO NOTE <u>ALL</u> FREQUENCIES THAT APPLY TO YOUR TEAM		
<b>Frequency</b>	<b>Channel/Band</b>	<b>Power (mW)</b>
5.0 GHz - 802.11a	Any	32mW(a)
2.4 GHz - 802.11b/g	Any	100mW(b)/80mW(g)

## 4. Control Method and Human-Robot Interface

The robot is remotely tele-operated, providing large amounts of information and feedback to the driver to prevent human error via a sophisticated user interface.

The control system uses a PlayStation 3 controller as this is familiar to many people and helps to make the system more intuitive for the user. As the layout is familiar, the user will not need to learn the position of the buttons, just the actions they perform, which is shown to users via a controller layout much like that of video games. This makes the control system very easy for new users to learn.

All major functions are controlled via the remote controller, including:

- The robot tracks
- The robot arm
- The rotating flippers

There are several modes that can be set by the user that determine the control system they prefer. In the case of the arm, there are three control methods – all of which can be accessed from the shape buttons on the remote. These include:

- ‘World Mode’ – in which the arm is controlled using a cylindrical coordinate system. The user can dictate movements in the  $r$ ,  $z$  and  $theta$  directions using the analogue sticks. This is useful for searching for victims.
- ‘Fly Mode’ – the user can aim the head at any object and then move in the new Cartesian co-ordinate frame based upon the head’s direction (i.e. the user can aim at an object and then move towards it in a straight line). This is very useful for accurate manipulation.
- ‘Joint Control’ – if desirable for the situation, the user can also control each joint separately. This could be appropriate in difficult manipulation scenarios but is generally not needed. It can be useful just in case the user has a particular preference for joint control.

The ‘World mode’ and ‘Fly mode’ are possible due to the inverse kinematics that has been implemented this year. The movement is kept smooth using linear interpolation which keeps the arm moving on a straight line path between target points. This has greatly improved control and gripping accuracy by allowing the operator to focus on the task at hand instead of thinking about which robot joint should be moved next.

The robot also has several pre-set positions for common tasks which can be accessed from the D-pad (4 directional buttons) on the controller. These pre-set positions simply aid the user by removing the need to move back to a desired position after a task has been performed. For example, the user can quickly place the arm back into the driving position using the ‘Down’ button which brings the arm back within the footprint of the robot and facing forward for the best driving view. There are other pre-sets such as the ‘search view’ in which the head is raised and the ‘limbo’ position which is useful in looking down pipes.

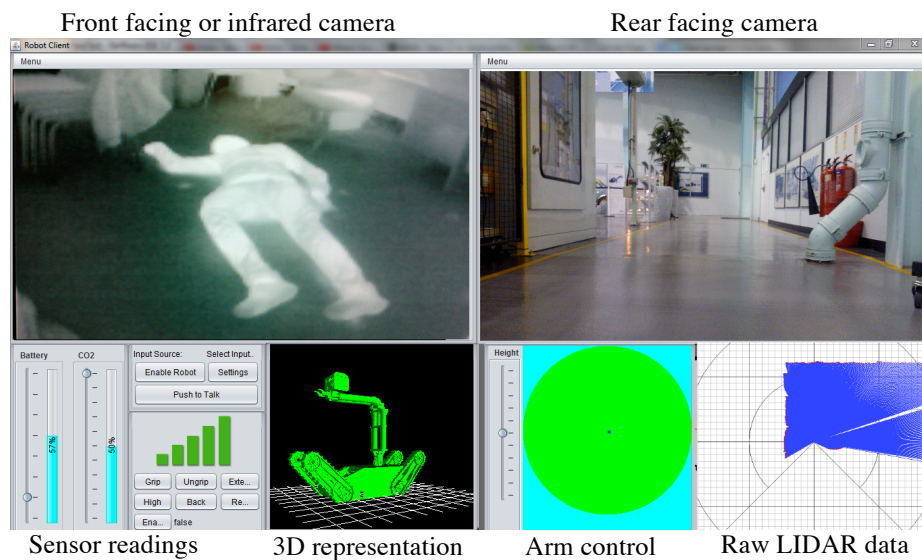
In terms of driving, the user has two options (both of which can again be set from the controller):

- ‘Tank’ mode – in which the user can operate each individual track using either the left or right analogue stick. This has been a preferred option for

many operators as it provides intuitive driving and allows for on-the-spot rotations.

- ‘Normal’ mode – this mode allows the user to control both tracks from one analogue stick. This allows the user of the arm whilst the robot is moving – without needing to switch to an arm control mode.

The flippers are simply operated using the shoulder buttons on the PS3 controller - the right buttons for the right flippers and left buttons for the left flippers. The flippers are very important in enabling the robot to manoeuvre over step fields and maintain balance on steep climbs, so accurate and intuitive control is critical.



**Fig. 2.** Graphical User Interface (GUI) used to control the robot

As tele-operation creates the risk of driver error, as much information as possible (and practical) is provided to the driver via the user-interface (Fig. 2). It is vital that this information is presented in an easily understood manner – which is why there is a heavy focus on diagrams, sliders and warning messages. The robot itself also has a programmed error checking function which prevents the user from making serious mistakes and provides feedback to the user with regards to the error they tried to make.

### Front and Rear Cameras

The front and rear IP cameras (Axis M1054) provide front and rear real-time footage to the operator with very minimal lag. These are the main aids for driving and victim identification. The front camera feed on the interface also includes two-way sound which is used to communicate with victims (over the headset). The cameras are positioned to allow the operator to see obstacles, victims and also provide information as to the current position of the flippers.

### 3D Representation

The 3D graphic is a critical driver aid. It provides several pieces of key information including:

- Real-time arm and flipper positions
- The robot orientation about  $x$ ,  $y$  and  $z$  axes– with the use of Inertial Measurement Unit (IMU) data
- The position of the robot's centre of gravity
- The system also highlights errors – an error function is checked before the user attempts a movement or command in case it will cause the robot to fail (either by colliding the arm with a part of the robot, moving to a position that will shift the centre of gravity to the point at which the robot will tip, or by trying to exceed joint angles). The data is then fed back to the user by changing the colours of specific joints or displaying error messages on the graphic which show the error that would have occurred.

### **Arm Control diagram**

A new method for controlling the arm has been developed in which the user can control the arm using the GUI. The user is shown all positions the arm can move in the global co-ordinate frame and can select any point where they would like the arm to move; this command is then sent and acted upon. There is also a bar to control the height of the arm so the user can move the arm to any possible position with two clicks.

It is thought that this method would be particularly desirable when combined with a tablet PC which uses touchscreen technology. The user is not restricted to using the controller and can instead use the touchscreen alone to control the robot. In this case, the operator could use the robot standing up and just holding the tablet.

### **Infrared Camera**

The robot has a front-facing infrared (IR) camera (FLIR Photon 160) in the head which is a key tool for finding heat signatures of victims within rubble. The operator can switch between seeing the front IP camera or the front IR camera on the interface by clicking on a button or a pressing keyboard shortcut.

### **LIDAR data**

Raw LIDAR data is displayed on the user interface as another driver aid. It helps with navigation and gives perspective to the camera views. It was found during testing that a sense of distance when remotely driving is distorted. For example, it is hard to evaluate whether the robot will fit through a door or a narrow space. This is where a laser distance sensor greatly helps.

In the future it is hoped that the LIDAR data and the 3D representation can be combined so that an operator could be driving from a 3<sup>rd</sup> person view in a dynamically generated 3D map.

### **CO<sub>2</sub> data**

The interface has a slider which shows the real-time CO<sub>2</sub> readings from the sensor. The slider allows the user to make a mark of the ambient room CO<sub>2</sub>. When the graphic moves above the mark, it suggests a victim is present.

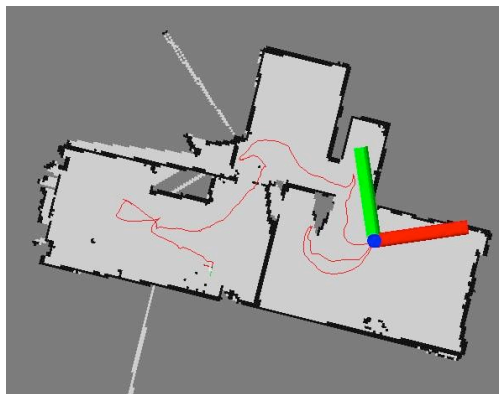
### Battery Gauges

It is crucial that the robot does not run out of battery whilst in operation, so the operator is shown the current battery voltage so that they get the robot back to a retrievable area before the batteries run out.

## 5. Map generation/printing

A Hokuyo URG-04LX laser scanner and an XSens MTi Inertial Measurement Unit (IMU) are present on board the robot. These should provide sufficient data to drive a Simultaneous Localization and Mapping (SLAM) algorithm in order to generate a map. The IMU allows LIDAR tilt to be measured and compensated for in the algorithm to obtain a cleaner result. Several approaches have been investigated, in particular:

- Winkvist Hexakopter SLAM [10.] developed within University of Warwick for 3D mapping of indoor structures from a UAV platform;
- Hector SLAM (Fig. 3) [3.] developed specifically for RoboCup arenas;
- tinySLAM [1.] developed with a small computational footprint in mind.



**Fig. 3.** A map of several rooms generated by Hector SLAM utilizing LIDAR data.

It was found that Hector SLAM works best with the existing sensors but integrates poorly with the WMR software platform. Furthermore, outside a structured (competition-like) environment it was found that the system produces rather poor results. This is due to the limited range of laser scanners (4 m in the case of Hokuyo URG-04), inability of the system to cope with a significant change in height (e.g. stairwells) and a significant loss of accuracy in the presence of moving objects such as people or doors. Thus it was concluded that such a system would not be of the most practical value in a disaster scenario, so team efforts this year were more focused on increasing the general reliability of the vehicle. Therefore, WMR is unlikely to have a working mapping system ready in time for the competition.



## **6. Sensors for Navigation and Localization**

The robot has five sensors that the operator can utilize to navigate the robot. Two webcams are mounted on the robot. One is fixed on the rear of the robot and the other on the front of the movable head. These both have a small lights attached and give the operator a visual image of the surrounding area. Due to this arrangement the robot can be easily driven both forwards and backwards. An IR camera mounted in the head is also used to give an indication of surroundings in the form of a thermal image.

Placed on the main body of the robot is a LIDAR module. This is used to create a 2D scan of the arena to give additional information to the operator. This is especially useful when navigating narrow spaces as it gives the operator a better sense of distance than just the camera images.

When traversing over rough and uneven terrain it needs to be ensured the robot will not topple over at any point. For this reason an XSens IMU is mounted inside the body to give an indication of the orientation of the robot. This is fed to the GUI and the operator is given a visual representation of the robots orientation to ensure the robot is not on the brink of toppling over. This visual representation also displays the position of the robots flippers, arm and head. These are tracked using a number of encoders built in the joints.

With the information from all these sensors the operator can build up an image of the surrounding area.

## **7. Sensors for Victim Identification**

Victims can be identified visually via either of the two IP cameras or the 2D LIDAR scan as mentioned in the previous sections. Furthermore, the infrared camera image can be used to quickly spot human body heat signatures, even if the victims themselves are obscured under a certain amount of rubble. In addition to these sensors mounted in the head is a CO<sub>2</sub> sensor that indicates an intensity level of the gas in the surrounding area. This is used to alert the operator via the GUI in case human breath is detected. The two IP cameras also incorporate a microphone and speaker to enable a two-way conversation between victim and operator. Because of the full duplex communications the operator is always able to hear (e.g. cries for help). By correlating the inputs from the various victim identification sensors (i.e. movement, sound, heat and breath) the operator can quickly identify the location and state of a victim. The robot's gripper can then be used to deliver a bottle of water, medicine, food, radio beacon or any other item to relieve the victim.

## **8. Robot Locomotion**

The WMR search and rescue robot is driven by two tracks (one on each side) which are powered using two Maxon RE-50 motors with rotary gearboxes. This gives the robot high torque which means it can easily traverse slopes of up to 45 degrees

and overcome most terrains. The track itself has a large tread depth which allows it to produce excellent grip under most conditions. This enables the robot to easily climb over obstacles (e.g. piles of rubble). The stability of the robot has been improved this year by lowering the centre of gravity.

The robot also has four flippers, two at the front and two at the rear; these are designed to give the robot a length equal to four stair steps thus increasing its traction when travelling up and down them. These flippers are driven from the same motor as the tracks and the left and right sides are rigidly connected. Both the front and back flippers can rotate 360 degrees thus allowing them to shape the tracks to the terrain. The flippers have enough power to lift the robot off the ground to increase the height it can reach. This feature can also be used to traverse deep puddles as the robot shell is not yet fully waterproof. Because of the flipper chain drive design they soften impact in case the robot drops from a significant height thus preventing damage to the internal systems. This locomotion system won the best in class award for mobility in the RoboCup German Open 2012 (Fig. 4).

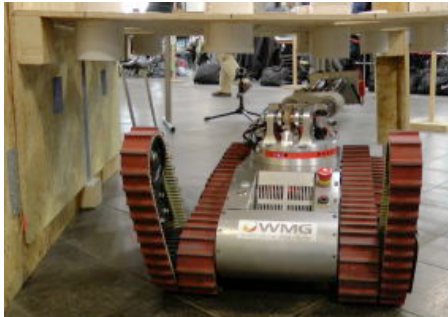
The robot drive can be controlled in two ways. A single analogue stick can be used to control both tracks. This is useful on easy to moderate terrain and frees up the other analogue stick for other functions. On more challenging terrain a finer control is achieved by using an analogue stick for each track.



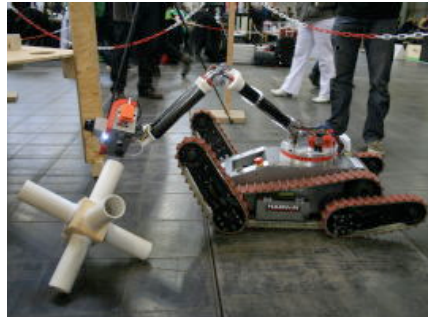
**Fig. 4.** WMR robot overcoming red zone step fields in the 2012 German Open Mobility Challenge.

## 9. Other Mechanisms

The most prominent feature of the WMR robot is its mechanical arm with 5 degrees of freedom (DOF). The arm has been designed to be as lightweight as possible to reduce the possibility of toppling. It uses three motors and two servos to give its degrees of freedom, the servos are based in the head to give tilt and pitch, whereas the motors are used to rotate and base and extend the arm. This system won the best in class for manipulation in the German Open 2012 as it identified all the points on the table shown below (Fig. 5) and two of the points on the star (Fig. 6) before running out of time.



**Fig. 5.** WMR robot under a low table



**Fig. 6.** WMR robot looking into a tube

The arm is controlled using inverse kinematics and linear interpolation, which allow it to move in a smooth line from its original position to its destination. The arm can be controlled using the joysticks used for driving by switching modes on the controller. This allows the driver to navigate obstacles that may be in the way, for example to look behind a wall. An alternate method of control uses a simple graphical method where the operator inputs the height on a scale and the polar co-ordinate position by clicking on a circular graph giving the  $r$  and  $\theta$  coordinates.

A gripper is also present at the end of the arm. This has been designed specifically for picking up standard 500 ml bottles. However, it can also be used to pick up and deliver other small items such as packets of food, medicine or a radio beacon. The inverse kinematic control of the arm allows the operator to grip these items quickly and accurately.

## 10. Team Training for Operation (Human Factors)

Last year it was found that poor operator training was one of the few pitfalls of the WMR team in the German Open. In the past the team has been unable to sufficiently train the team members before the competition. This is because each year a new team is tasked with redesigning the robot from October and the project has to be finished by the start of the third university term (end of April, beginning of May) and the German Open is held in April. The team member tasked with driving only gets training once the robot is built and tuned and as this project has large lead times the test driving is normally done just before completion. This year the robot will still have to

be built for the project deadline, however as the World RoboCup is held in June, the driver will have two months to practice. WMR own a step field and obstacles similar to those of the competition and thus can practice in a controlled environment. Another testing method the WMR have at their disposal is Northrop Grumman Remotec's testing facilities (an outdoors obstacle course with building elements). This will give the test driver experience with different obstacles, more like those in a real-life situation.

It was also understood that situational awareness of the operator last year was poor due to non-optimal user interface design. The interface has been heavily redesigned this year. This helps team training as the system is aims to be intuitive to those operating it. The layout of the PS3 controller used as the main input device is familiar to many. Along with a well thought-out controller mapping this makes it easy for anyone to learn the controls. Additionally, the 3D representation and LIDAR feedback present the complex configuration and state of the robot in an easily perceivable way, thus improving distance awareness and drivability.

For a new operator it is beneficial to have radio control model or video game experience, however, this is not necessary. The robot was presented in the Imagineering fair [7.] where it was successfully used by children as young as 10 without any training whatsoever. More advanced features, such as successful, quick and accurate manipulation of the arm require some practice, but this has been made significantly easier by implementing inverse kinematics.

## **11. Possibility for Practical Application to Real Disaster Site**

The system is approaching a practically deployable solution. Our recent partnership with Northrop Grumman Remotec is a considerable step towards this goal. This year WMR focus has been particularly on improving the robustness and reliability of the platform. This includes a certain level of weatherproofing. Outdoors testing in an assault course intended for bomb disposal robots is planned later this year, courtesy of Remotec. This will prove the robustness of the robot itself as well as the usefulness of the improved control interface. Thus the physical components of the system (robot and operator station) could be deemed ready for real operational use.

There are, however, weaknesses that would complicate a real deployment. First, the battery running time is only around 25 minutes during intense operation or 40 minutes during less intense operation. Even though battery holders have been redesigned and batteries are now very quick and easy to swap, this could pose a problem in a real disaster zone if the mission time is longer. Warnings have been implemented so the operator can return the robot out of the dangerous area in time to swap the batteries, however, it is understood that the half an hour running time is insufficient. This could be addressed in the future by increasing battery capacity as well as reduction of power requirements. Second, the communications are provided by an off-the-shelf Wi-Fi router. While this works very reliably over short distances the range is very limited, especially indoors not in line of sight. In the future other communication options should be investigated.

## 12. System Cost

The total parts cost of the WMR system is around £11 000 (Table 1). It must be noted, however, that this does not include the costs of design time, in-house manufacturing (e.g. machining, assembly) or software development.

**Table 1.** Costs of the WMR robot component parts

Component	Cost (£)	Part Number	Supplier
<b>Chassis</b>			
Metal for chassis space frame	72		Ravenace Metals
Water Jetting for chassis space frame	80		AquaJet
<b>Electronics</b>			
Flipper Encoders	25.13		Future Electronics
CO <sub>2</sub> 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	<a href="http://www.ebuyer.com">www.ebuyer.com</a>
Axis M1054 HD IP network camera x 2	538 (£269 x 2)	0338-003	<a href="http://www.networkwebcams.co.uk">www.networkwebcams.co.uk</a>
ASUS RT-N56U router	82.54	RT-N56U	<a href="http://www.systo.co.uk/">http://www.systo.co.uk/</a>
Dynamixel Robotics RX-64 Servo	180.50	HN05-N101	<a href="http://robosavvy.com">http://robosavvy.com</a>
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	<a href="http://linitx.com/">http://linitx.com/</a>

<b>Mechanical</b>			
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 battery cases)	570		Dr Greg Gibbons from WMG, University of Warwick
Shell x 2 made from ABS	630		Bay Plastics Ltd
Lithium Polymer Batteries (x4)	180 (4 at £45 each)		Various suppliers
<b>TOTAL: £10,937.84</b>			

### 13. Lessons Learned

To be completed after the competition.

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