The Open Academic Robot Kit: Lowering the Barrier of Entry for Research into Response Robotics

Raymond Sheh
Department of Computing
Curtin University
Bentley, WA, Australia
raymond.sheh@curtin.edu.au

Haldun Komsuoglu
Robolit LLC
Philadelphia, PA, USA
haldun.komsuoglu@robolit.com

Adam Jacoff
Intelligent Systems Division
National Institute of Standards and Technology
Gaithersburg, MD, USA
RobotTestMethods@nist.gov

***Abstract*—Open Source Software is a vital catalyst within the academic robotics community. Frameworks built on open software, like the Robot Operating System (ROS) and the family of libraries that have grown up around it, ease the process by which researchers and students can create integrated, working systems. This has allowed those who have little experience or academic interest in areas like software engineering, communications or artificial intelligence, to make use of others' contributions and build on them in their own areas of expertise. The Open Academic Robot Kit seeks to foster a similar community around open hardware designs for flexible, customised, low cost academic and research robots. It leverages recent advances in 3D printing and the mass production of microcontroller boards, sensors, smart servos and other components for the Maker community. The emphasis is on the ease with which other researchers, students and members of the wider hobbyist and Maker communities, in different fields, may contribute, replicate and extend the designs.**

I. Introduction

The Open Academic Robot Kit is a family of community-developed designs that lower the cost, effort and expertise required to produce small, yet interesting, research and education robots. It leverages recent advances in low cost rapid prototyping equipment and the increasing popularity of components catering for the "Maker" community. It aims to do for robot hardware what robot related open source libraries have done for algorithms – enable those who have expertise in an area to package up their capabilities and make them available for others to reproduce and extend [1].

Every day, all around the world, responders must approach known or suspected hazardous situations in order to render them safe and save lives. Examples of hazardous situations include explosives, hazardous substances and unstable structures. Robots are increasingly being used to address these situations, with the goal being to allow responders to "start remote and stay remote". Unfortunately, the current state of response robots often fall short of this goal. In some cases, this results in the hazard being left unaddressed. In others, human responders must take the risk and approach themselves.

In our work on developing test methods for response robots, we have identified gaps in currently deployed implementations that can be addressed by capabilities that already exist within academia or are the subject of current research. The RoboCupRescue Robot League (RRL) [2] was started over a decade ago to encourage research in this field, evaluate the state of response robots in academia and disseminate the challenges and best-in-class capabilities in response robotics. This competition has enjoyed considerable success towards these goals. Teams have progressed beyond the lab, with several demonstrating and testing robots alongside responders at responder training events. A few have even deployed robots in real response situations, including the Fukushima Daiichi nuclear power plant disaster [3].

While the competitions have been highly successful in catalysing academic research in this field, the barrier of entry for many teams, especially those with significant contributions to make in domains outside of mechanical engineering, are significant. Groups that specialise in perception, artificial intelligence or human-system interaction often lack the necessary breadth of skills in mechanical and electrical engineering to produce a robot that fully utilises their capabilities in the lab, let alone in competition or deployment. In order to demonstrate their work, these teams must either devote considerable resources to purchasing and modifying suitable robot platforms, or must compromise and improvise with platforms that limit their capabilities.

Initially, the primary aim of the Open Academic Robot Kit is to provide these teams with low-cost, flexible, easy-to-construct robot platforms that allow them better develop and more fully demonstrate their capabilities. A secondary objective is to promote collaboration around the world, as different groups contribute to the designs. The Open Academic Robot Kit also reaches beyond the academic research community and has several characteristics that are interesting to educators at the high school and undergraduate level.

II. Related Initiatives

Many initiatives and projects have adapted open source principles to hardware with the aim of lowering the barrier of entry into particular fields. There are particularly salient examples that, with the advent of ad-hoc public collaboration tools (such as forums of various sorts), social media and the "Maker" movement, have gained considerable traction. The focus of this paper is on an overall initiative that builds a community of different robot designs, rather than a single robot. Thus while there are several very promising single-design open source robot initiatives, especially among the humanoid robotics community, a detailed discussion of these falls outside the scope of this paper.

One particularly high impact project is the Arduino[1] microcontroller platform. Arduino started as a single reference board and programming environment, designed to lower the cost and complexity of using microcontrollers. Initially a student academic project, the Arduino was unique in its time for its aim of being both open and inexpensive. A major contributor to the success of the Arduino was the ability to freely improve and redistribute the design commercially. It is now possible to purchase a wide variety of Arduino-compatible boards and associated add-ons from vendors all around the world, most of whom have no connection to the original developers. The Arduino has catalysed advancements in a whole host of domains simply by lowering the barrier of entry so that those who can contribute in related fields don't need to also become expert in managing microcontroller development.

Like the Arduino, the RepRap project has also been having an impact in lowering the barrier of entry into a new field, in this case additive manufacturing or 3D printing. Leveraging the Arduino as a low cost, accessible controller, the RepRap project sought to produce an initial design that was not necessarily the best 3D printer, or even a particularly good 3D printer. Rather, the goal was a 3D printer that was low cost, easy to reproduce, easy to improve and released under a permissive license that allowed others to make and sell their own improvements. Like the Arduino, the RepRap project has spawned a huge number of 3D printers that range from hobbyist to professional, build-it-yourself to ready-to-run. In the process, 3D printing has been made available at price points and skill levels unimaginable only a few years ago. And like the Arduino, the RepRap has also catalysed advancements in a whole host of domains that are related to 3D printing, be it development or application.

The Open Academic Robot Kit builds heavily on both of these projects. The initial designs all make use of Arduino microcontrollers and use the Arduino programming environment. It is anticipated that subsequent designs will do likewise. The initiative is only possible due to the existence of low cost 3D printing equipment, made possible by the RepRap project. The Open Academic Robot Kit also seeks to harness the same spirit of community development that gave the Arduino and RepRap projects such a large impact in lowering barriers of entry. In the process, it is hoped that this will also catalyse the development of solutions to the many related problems in robotics in general, and response robotics in particular.

The Open Academic Robot Kit is far from the first initiative to seek to leverage the open community development model for the advancement of specific areas of robotics[2]. A huge amount of work has already been done in open software for robots [1], this discussion will focus on open hardware.

In terms of ubiquity and impact, it is hard to ignore the contribution of Lego Mindstorms[3]. The platform itself is not open – the individual components are proprietary and single-vendor. However, it has been a tremendous catalyst for community development and sharing of robot designs and capabilities, especially among hobbyists and at the primary and secondary school levels. Lego Mindstorms, and the communities and competitions that have developed over the various generations, have demonstrated that it is possible for a set of common hardware, electronic and software components, available internationally, to catalyse development in a huge number of areas.

Lego Mindstorms is of course not without its shortcomings. While it is tremendously accessible from a skill level perspective, the financial cost of entry can be limiting. It can also be impractical (although by no means impossible) to create robust mobile robots much larger than 30cm in any one dimension owing to limitations in both structural integrity as well as the strength of the actuators. Complex mechanics, such as wrist joints for robot manipulators, can also be difficult to implement. At the secondary school level, the Open Academic Robot Kit seeks to provide a natural progression from Lego Mindstorms, for students who have run into these issues. Indeed, designs of the Open Academic Robot Kit can be quite naturally welded to Lego bricks[4], allowing components of the Open Academic Robot Kit to be used in existing Lego Mindstorms designs and vice versa.

Application specific initiatives are also gathering considerable traction. One example that is also relevant to the response robotics community is the Ardupilot[5], an Arduino-based add-on controller for mobile platforms. This controller is particularly popular among the aerial robotics community. It allows researchers who don't have access to microcontroller or control engineering expertise to integrate working aerial robots, at a low cost and with the flexibility that allows them to do their research. Another example is the Yale OpenHand[6], a design for a low cost hand-type gripper, backed by a project that seeks to use the open source community to foster a collection of different, useful designs and variations.

III. Principles and Properties of the Open Academic Robot Kit

All of the designs of the Open Academic Robot Kit are free for anyone to recreate, improve and redistribute as-is or improved so long as they cite the original design and allow others to similarly redistribute and improve on the design. To this end, each design in the Open Academic Robot Kit should satisfy the following principles.

All parts that are not electronic (and are not common fasteners like nuts and bolts) can be 3D printed in ABS plastic on a low cost (sub-$1,000) single-extruder fused-filament 3D printer. The primary constraints are size (fitting within a

[1] `http://www.arduino.cc`

[2] The Wikipedia entry `http://en.wikipedia.org/wiki/Open-source_robotics` maintains a partial list of open source robotics projects.

[3] `http://mindstorms.lego.com/`

[4] Acetone may be used to create strong plastic solvent welds in acrylonitrile butadiene styrene (ABS) plastic, such as between Lego bricks (which are made of ABS plastic) and the ABS plastic commonly used in low cost desktop 3D printing.

[5] `http://ardupilot.com`

[6] `http://www.eng.yale.edu/grablab/openhand/`

$200 \times 200 \times 200$ mm cube), minimum feature sizes and the inability to use multiple materials (for printing or support)[7].

Designs for all aforementioned parts, in easily editable and printable form, are released under the CC-BY-SA license[8].

All fasteners are either M2 or M3 bolts, nuts and washers (or 1/16" and 1/8" US bolts, nuts and washers).

All electronic parts are readily available either off-the-shelf or by mail-order from anywhere in the world.

Critical parts, such as control boards or smart servos, that are not themselves already released under an open license, should have at least one practical alternative option from a different manufacturer in case the prescribed part becomes unavailable.

All basic code and libraries necessary to run and demonstrate the capabilities of the robot, so that others may write code for it, are released under the GNU General Public License[9]. Original code authors may, of course, choose to dual license their code or produce additional code to be released under an alternative license.

All of the designs in the Open Academic Robot Kit should be accompanied by at least sufficient documentation, released under the CC-BY-SA license, to allow a "reasonably skilled" person to recreate the robot. Naturally, the definition of "reasonably skilled" will vary depending on the nature of the robot.

Through these principles, the Open Academic Robot Kit exhibits some unique properties and facilitates a variety of innovative use cases.

A. *Competitions*

Physical robotics research competitions [2] often have a significant barrier of entry, especially for teams specialising in software and algorithms. A competition that makes use of the Open Academic Robot Kit allows all teams to build directly on the best performing robots from the previous year. The effect is similar to that caused by the proliferation of open source implementations of algorithms such as vision, mapping and planning. Teams will be able to build on the work of others where they have little expertise, allowing them to concentrate on areas where they have expertise. This maximises their ability to contribute back to the research community. By ensuring that the winning robots of the previous competition can be more easily replicated, the performance of the competition as a whole can only improve. This effect can also happen within the context of a multi-day competition with teams sharing improvements to their robots. Competitions for advancing the state of a specific research area exhibit properties that make this effect particularly pronounced. We describe this in more detail in [2]. In the context of the RoboCupRescue Robot League we have found the following features to be particularly useful.

- The whole competition emphasises a culture of teams competing against the application rather than each other. For example, teams never go head-to-head and the competition is all points based, allowing teams that specialise in different aspects of the competition to compete.
- Teams with specific areas of expertise are explicitly encouraged to compete, even if they cannot field a fully competitive system. This is done two ways. Teams that qualify after the preliminary round are encouraged to combine with a team that did not qualify but may have specific capabilities that they lack. At the end of the competition a separate Best-in-Class competition is held that tests specific capabilities.
- Teams that actively share their capabilities are recognised and rewarded through official awards and wider use within the research community, improving publication citations.
- Teams with Best-in-Class capabilities are encouraged to share their capabilities at academic summer schools, run a few months after the competition[4].

B. *Educators, Hobbyists and Makers*

Robots are being found to be increasingly useful in a classroom setting, be it primary, secondary, tertiary or mature-age. Where there is a design or problem solving component, having the freedom to print custom parts to address specific challenges can have significant benefits over the use of "construction kit" style approaches. The workflow from idea through computer-aided-design (CAD), design-for-manufacturability (DFM) and prototype iteration aligns closely with that used in industry. Of course, these advantages are simply the advantages of using rapid prototyping equipment in the classroom. Where the Open Academic Robot Kit is advantageous is in cost, logistics and collaboration through time and space – that is, between cohorts and between geographically separated groups.

The example designs and, it is anticipated, many of the subsequent designs will make use of common electronic components such as Arduino-compatible microcontrollers and Robotis Dynamixel AX-12 smart servos. While the AX-12 servos are only available from one manufacturer, they are readily available. Should they become unavailable, the hardware designs and sample software make it easy for anyone to modify to suit similarly sized replacements. A wide variety of different robot designs, for different purposes, can be constructed from these standard parts, much like how many different robot designs may be constructed using a construction kit. This means that it becomes possible to stock larger quantities of a few different parts. This reduces cost by providing some economies of scale and making supplies easier to track, knowing that they may be used for a large number of different designs. This is in contrast to many current custom robot kits, which often require different control boards, different servos, use different communication protocols and software libraries and so-on.

This potential for standardisation on parts also means that each cohort can easily build on the work from the previous. In a design based unit, this results in a library of parts that future students can easily make use of between disciplines. For example, art and design students can benefit from components produced by engineering students and vice versa. The option

[7] It can be hard to tell if a given design will print well on a fused-filament printer. It is recommended that designs be test-printed before contribution.

[8] `http://creativecommons.org/`

[9] `http://www.gnu.org/`

to use common protocols and libraries also allows the easy integration of different projects.

The Open Academic Robot Kit is also an international forum where such designs can be exchanged, with the aforementioned design and philosophy principles making it easy to extend each other's developments. Ad-hoc collaborations will emerge spontaneously. A design for a mobile manipulator robot in Australia might be extended by an undergraduate class in Thailand for developing a better gripper. That design might be used by a German PhD student to develop behaviours that require a more complex embodiment than is available off-the-shelf. A Japanese hobbyist might adapt the design for alternative smart-servos of a similar size. All of these groups can then benefit from each others' developments.

C. Responders

The original aim of the Open Academic Robot Kit was to make it easier for those who can contribute to advancing the state of response robotics to do so. By definition this will already have a benefit for responders. In addition, the Open Academic Robot Kit allows them to better understand the capabilities that exist within academia. In our work on the DHS-NIST-ASTM International Standard Test Methods for Response Robots, one common issue we encounter is the problem of communication of operational needs and emerging capabilities between the responder community and the technical community. The Open Academic Robot Kit provides a way in which these capabilities may be demonstrated in a way that may speak to responders more easily than if it were built from a construction kit, or shoehorned into a robot that is only partially suitable. Examples of such capabilities include intuitive control of high degree of freedom manipulators, aids for situational awareness and mechanical and electrical infrastructure to deploy novel sensing methodologies.

While the robots in the Open Academic Robot Kit may not fully satisfy robustness or reliability requirements for full deployment, demonstrating these capabilities in prototype form, perhaps at a reduced scale, can be tremendously helpful as a communications tool. When responders see the value in such developments, it is inevitable that pressure will be placed on industry to incorporate these developments.

Ultimately, however, the model of the Open Academic Robot Kit can be extended beyond the purely academic. The Open Academic Robot Kit also paves the way for just-in-time, custom purpose, low cost robots for actual deployment. Two major issues with current response robots are that they are necessarily a compromise as they must carry out many different missions and they need extensive, unique spare parts inventories and associated logistics. An Open Response Robot Kit will consist of a logistics unit, such as a shipping container, containing an inventory of standard parts, 3D printers, feedstock and a catalogue of robot designs and software. When disaster strikes, such as an earthquake or industrial accident, the perfect robot can be produced on-the-spot, using performance data gathered within the standard test methods to make their decision. These robots will be inexpensive, easy to repair and similar in their control methodology. It is hoped that the best robots from the Open Academic Robot Kit may become the prototypes that, along with their developers, feed into a future Open Response Robot Kit.

IV. Example Designs

This section describes the first three designs have been implemented using the principles of the Open Academic Robot Kit. They may be downloaded from `http://www.oarkit.org/`. Two of them are mobile robot bases while the third is a 5 degree of freedom (DOF) manipulator. All three robots are designed to facilitate the development of novel solutions to problems that face responders while being inexpensive and accessible to students, researchers and developers with limited traditional mechanical and electronic engineering expertise. These robots were not designed to be the best platforms for any given task, or even particularly good platforms for any given task. They are designed to be interesting starting points for learning about and developing further capabilities in robot control, mobility and manipulation in ways that are difficult using more conventional prototyping techniques. The plastic parts for all of these designs have been successfully printed in ABS[10] plastic on a first-generation Solidoodle 3 printer, purchased for approximately $800 USD in early 2013. This printer is representative of the capabilities of current low-cost desktop fused-filament printers[11]. All parts will fit within a $200 \times 200 \times 200$ mm cube and have been designed to be compatible with the minimum size, tolerance, support material and maximum overhang of such a printer.

A. Emu Mini – a simple mobile platform

The Emu Mini, shown in Figure 1, is based loosely on the "Emu" robot fielded by the Team CASualty RoboCupRescue Robot League team [5]. A basic skid-steered four-wheel-drive platform, it possesses a high level of mobility due to its ability to shift its centre of gravity by moving a heavy sensor head. This sensor head is also a stabiliser, preventing the robot from tipping over. The overall robot platform is 29 cm in length including 13.5 cm wheels. The wheels are designed to grip on rubble-like terrain while retaining the ability to skid-steer with relative ease. As ABS can slide on hard surfaces, the wheels are covered in layers of "tool dip", a rubber-like compound. Each wheel is driven by a separate gearhead motor, eliminating a complex drivetrain. The length of the arm is variable. Balancing the centre of gravity is part of the challenge in setting up and controlling this robot to maximise its performance on the task at hand. Testing of the robot within the 60 cm scale DHS-NIST-ASTM International Standard Test Methods for Response Robots is ongoing. The robot has demonstrated the ability to overcome the half-height symmetric stepfields (5 cm high blocks) [6] as well as stair steps with a height of 10 cm.

1) Basic Platform: The list of parts and $USD prices at time of purchase for the Emu Mini, plus arm and pan-tilt unit, is shown in Table I. For space reasons we have omitted full parts and price lists for subsequent robots, for full details please see the project website, `http://www.oarkit.org`. The total cost of parts for basic platform was $350.00.

[10]Polylactic acid (PLA) plastic may also be used. However, the resulting parts cannot be welded together using acetone and are of slightly reduced strength compared to ABS.

[11]Better printers can yield better results. However, most desktop printers share similar limitations of size, resolution, tolerances and overhang. We evaluated the use of UV cured resin printers (costing over $100,000.00 USD) and found that, for this purpose, the advantages were minimal given the cost.

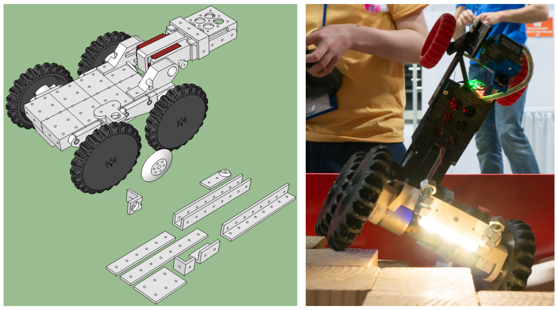

Fig. 1. The Emu Mini. Left: Rendered, alongside optional components to extend the arm and mount the pan-tilt unit. Right: As implemented driving over the 60 cm scale stepfields.

TABLE I. THE PARTS AND PRICE LIST FOR THE EMU MINI ROBOT.

\$133.00	4× 12 V gearhead motors and adapter hubs
\$57.00	12 V 12 A dual channel motor control shield for Arduino
\$25.00	Arduino clone microcontroller board
\$36.00	Large RC buggy steering servo
\$9.00	Nuts and bolts, cabling, connectors
\$24.00	2× Standard sized metal gear servos
\$15.00	15 A battery eliminator (6 V DC-DC converter)
\$14.00	3S1P (11.6 V) 2.2 Ah Lithium Polymer battery
\$30.00	1 kg of ABS plastic filament for 3D printing (partially used)
\$7.00	"Plasti dip" rubberised coating (used to coat wheels for added grip)

2) Example sensing and control: The robot can be controlled via a standard 2.4 GHz remote control (RC) system, often used for model planes and helicopters. A wide angle car reversing camera serves as the only sensor, transmitting via a 5.8 GHz model aircraft video transmitter and receiver. A car reversing camera monitor is used to display the video. The total cost for these additional parts is \$209.00. An alternative control and sensing setup might be a Raspberry Pi with a Pi Camera and USB wireless LAN adapter, totalling approximately \$100.00. The robot can then be controlled via a computer or mobile phone and have the computation power for more advanced autonomy. Another option is to mount a mobile phone to the robot and make use of the phone's camera, accelerometers and other sensors. A USB serial or bluetooth connection may be used to allow the phone to control the robot. The robot may then communicate using wireless LAN or the mobile phone network.

B. Six-Wheeled Wonder – an excessively complex robot

The Six-Wheeled Wonder, shown in Figure 2, is a mobile platform that appears to be excessively complex. It demonstrates how a relatively complex mobility system could be produced using low cost 3D printing. It also facilitates research into novel ways of autonomously or semi-autonomously controlling high degree of freedom wheeled advanced mobility platforms. This robot is 33.5 cm in length including 9.5 cm wheels. The wheels and joints are all driven by Robotis Dynamixel AX-12A smart servos which can be controlled in position or continuously rotating velocity mode.

The robot can both skid steer through its six independently driven wheels, as well as tractor steer through front and rear independently steered axles with $\pm 15^\circ$ of motion. This allows the robot to turn smoothly without skidding. The front wheels can be raised and lowered together by flexing the spine of the robot $\pm 30^\circ$. It can overcome larger obstacles by first raising the front axles, driving onto an obstacle and then lowering them. It also allows the robot to turn more easily by effectively making the centre pair of wheels lower than the front and back. By pushing down with the front wheels, thereby raising the centre wheels, the robot effectively becomes four-wheel-drive, with the independent front and rear steering axles allowing the robot to "crab" sideways slightly as it drives forward and backward. This robot can even "walk" the front wheels onto an obstacle using this approach. Again, testing of this robot within the 60 cm scale DHS-NIST-ASTM International Standard Test Methods for Response Robots is ongoing. Like the previous design, this robot has demonstrated the ability to overcome the half-height symmetric stepfields and stair steps with a height of 10 cm by flexing its spine.

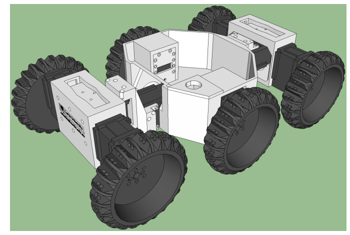

Fig. 2. A rendering of the Six-Wheeled Wonder robot.

The total parts cost for the Six-Wheeled Wonder was \$397.75. Note that in this example, only the basic platform cost is specified. The control is through a direct wireless interface to the Arduino; this control may come from a computer with a second Arduino and nRF24 radio module, or a custom controller described in Section IV-C3. Ordinary RC servos could be easily substituted for lower cost, however some would need to be modified for continuous rotation. Also the use of ordinary RC servos would add complexity – the data and power lines of the smart servos can all be connected in parallel, allowing the connectors to be daisy-chained.

C. 5 DOF Manipulator

The third design, the 5 DOF Manipulator, is shown in Figure 3. This is a 5 degree of freedom manipulator, designed to carry a lightweight payload such as a small camera. While it was designed to be mounted to the rear steering axle of the Six-Wheeled Wonder robot described in Section IV-B, it may also be mounted to existing robots, either to the bases or as an extension to a larger manipulator. It consists of three joints in the sideways axis (across the arm) followed by two joints at right angles. This provides limited ability to shift the end effector in the sideways axis. This is intended to be provided by the platform on which the arm would be mounted. The stowed dimensions of the arm are 16.6 cm wide, 23.5 cm long and 79 cm high. Fully outstretched, the arm can place the mounting surface of the final joint anywhere on an arc 55 cm from the axis of the first joint and 57.5 cm above the mounting surface. Again, testing of the robot within the DHS-NIST-ASTM International Standard Test Methods for Response Robots is ongoing. The robot has demonstrated the ability to easily clear the small scale "Pipestar" nodal directed-inspection task in roughly 2 minutes, when mounted on the rear axle of the Six-Wheeled Wonder robot as shown in Figure 3,

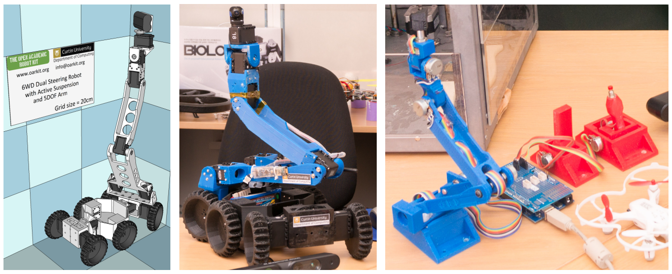

Fig. 3. The 5DOF Manipulator mounted onto the Six-Wheeled Wonder mobility base. Left: Rendering shown with Sony ActionCam mount. Centre: Shown with wireless camera. Right: Master arm and joysticks for controlling the robot arm and base.

equipped with a small search camera and controlled via the master-slave arm described in Section IV-C3.

1) Robot Arm: The arm itself consists of six AX-12A smart servos plus control electronics. For additional strength, two servos are used to actuate the first joint. Again, while ordinary servos may be substituted (with corresponding modifications to the mountings) the ability to daisy-chain the smart servos, along with their wider angle of motion compared to ordinary unmodified RC servos, makes them particularly advantageous. The arm can comfortably lift a payload of around 100 g through most of its range of motion and around 50 g when fully outstretched. The smart servos provide telemetry that includes the position and load on the individual joints of the arm. This allows students to work on interfaces that can intelligently plan or limit motions depending on load, for example. Total cost of parts for robot arm was $273.50.

2) Basic Transmitting Camera: The same camera described in Section IV-A2 may be used. These cameras are often fisheye in nature. This effectively implements foveated vision in optics – the edges of the frame are lower in resolution but provide situational awareness while the centre of the frame is expanded and higher in resolution. This provides a surprising level of visual acuity in the centre of the frame. However, fisheye images do require some practice to properly interpret due to this distortion. The total cost for this sensor package was $139.00. Alternatively, the arm can carry a small transmitting camera, such as a Sony ActionCam, which includes its own wireless LAN based transmitter. The camera can tap the arm's power supply through a light weight regulator, removing the weight of its battery.

3) Controller: Like the Six Wheeled Wonder in Section IV-B, the arm may be easily controlled using a second Arduino, connected to a computer and equipped with an nRF24 radio module. For a static arm, the AX-12A servos may be directly connected to a computer via a USB adapter. One interesting approach that has been implemented, however, is a master-slave arm, shown in Figure 3. The full sized design was scaled by 50% in each dimension and the joints modified to take potentiometers rather than servos, to produce the designs for printing the master arm. Each potentiometer was wired into the analogue inputs of an Arduino Mega 2560 clone that was also equipped with an nRF24 radio transceiver. By moving this master arm, the full sized slave arm would also move in a similar way. This allows for quite precise, intuitive control without the need to implement inverse kinematics in software. The cost of parts for the controller was $53.00 including parts required for controlling the Six-Wheeled Wonder base through two 3D printed joysticks (including one 2 DOF gimbal).

V. Future Directions

The designs described above are starting points, integrated and working systems, from which others may make incremental improvements on the basis of their expertise. These can include improving user interfaces, increasing payload, adding or changing functionality and so-on. One direction that is being actively pursued is the use of the principles of the Open Academic Robot Kit to prototype additional smaller arms that can be attached to existing response robots, to provide additional situational awareness. The Open Academic Robot Kit has also gathered interest from the arts community. It provides a way for arts students to access developments in autonomous behaviours, robot control and mechanisms that would otherwise be expensive or impossible for them to adapt and incorporate into their work.

These designs, and additional lower-cost examples, will form the basis of several pilot academic and community classes. It was demonstrated at the 2014 RoboCupRescue Robot League and RoboCup Junior Rescue competitions, where it was very well received and looks likely to form the basis of a transition competition between junior and major rescue competitions. It was also the example platform for the 2014 IEEE-RAS Response Robotics Summer School and Workshop[12] [4]. Several pilot teams will then build on these designs, or create their own using compatible components, for competition in the next RoboCupRescue Robot League and RoboCup Junior Rescue competitions, focusing on the Confined Space Challenge, a smaller arena with gaps of 60 cm and 30 cm, designed to represent the smaller spaces present in domestic environments.

References

[1] S. Kohlbrecher, K. Petersen, G. Steinbauer, J. Maurer, P. Lepej, S. Uran, R. Ventura, C. Dornhege, A. Hertle, R. Sheh, and J. Pellenz, "Community-Driven Development of Standard Software Modules for Search and Rescue Robots," in *Proc. IEEE Int'l Symp. on Safety, Security, and Rescue Robotics*, 2012.

[2] R. Sheh, A. Jacoff, A.-M. Virts, T. Kimura, J. Pellenz, S. Schwertfeger, and J. Suthakorn, "Advancing the State of Urban Search and Rescue Robotics through the RoboCupRescue Robot League Competition," in *Proc. 8th Intl. Conf. on Field and Service Robotics (FSR)*, Matsushima, Miyagi, Japan, Jul. 2012.

[3] K. Nagatani, S. Kiribayashi, Y. Okada, S. Tadokoro, T. Nishimura, T. Yoshida, E. Koyanagi, and Y. Hada, "Redesign of rescue mobile robot Quince: Toward emergency response to the nuclear accident at Fukushima Daiichi Nuclear Power Station on March 2011," in *Proc. IEEE Int'l Symp. on Safety, Security, and Rescue Robotics*, 2011.

[4] R. Sheh and H. Komsuoglu, "The 2012 IEEE Robotics & Automation Society Safety, Security, and Rescue Robotics Summer School: An Event for the Dissemination of the Challenges and Best-in-Class Capabilities in the SSRR Community [Society News]," *IEEE Robotics and Automation Magazine*, vol. Vol. 19, No. 4, 2012.

[5] R. Sheh, A. Milstein, M. McGill, R. Salleh, B. Hengst, and C. Sammut, "Semi-Autonomous Robots for RoboCupRescue," in *Proc. Australasian Conf. on Robotics and Automation*, 2009.

[6] A. Jacoff, A. Downs, A. Virts, and E. Messina, "Stepfield Pallets: Repeatable Terrain for Evaluating Robot Mobility," in *Proc. Performance Metrics for Intelligent Systems Workshop, NIST Special Pub. 1090, Aug.*, 2008.

[12] http://www.responserobotics.org