A Reconfigurable Robotic Exploratory Vehicle for Navigation on Rough Terrain

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Abstract. This paper discusses the development of a new family of reconfigurable robotic vehicles for use in exploration of the surfaces of Mars and other remote planets. The robotic vehicle is designed using modular reconfigurable hardware components and a software architecture that reconfigures its software capability based on hardware configuration. This paper will present an overview of the reconfigurable hardware and software architecture, as well as provide implementation results of mobile robot traversal on rough terrain.

1. Introduction

Exploration on unknown and uncharted planetary surfaces involves operating in an unstructured and poorly modeled environment. However, the lack of precise knowledge about the operating environment makes it impractical to incorporate every detail necessary to design robotic systems for multi-task execution. Unexpected changes in the environment, hardware sensor failures, or changes in task objectives can invalidate the original design. Most robotic systems are thus designed assuming complete knowledge of the task specifications and environmental constraints. This process results in robotic systems that are expensive to design as well as reduces the robot's ability to robustly deal with unplanned environmental changes or unexpected system failures.

In order to guarantee success of robotic missions for the future, technologies that can enable multi-rover colonization and human-robot interaction must be matured. The main hurdle with this focus is the cost and system complexity associated with deploying multiple rovers having the capability to survive long periods of time, as well as possessing multi-tasking capability. To address this issue, our research focuses on modularizing both hardware and software components to create a reconfigurable robotic explorer. This work thus allows the deployment of rovers on a planet's surface that can ensure robust operation in face of system reconfiguration, hardware failure, changes in task specifications, or alterations in environmental constraints.

The construct of our reconfigurable robotic explorer consists of two sets of components: a set of robotic transporters and a set of science modules. The robotic transporters, which are all identical, form our simplest autonomous explorers. These transporters are able to traverse rough terrain using on-board computational and power resources. Their symmetrical design with large wheels enables them to operate in any stable state and recover from drops off small cliffs. Conversely, the science modules have no mobility. They carry different science instruments and share only an identical interface. From these two modules, different mobility platforms can be assembled. Connecting two robotic transporters to each end of a science module forms a science-enabled explorer. Additional robotic transporters and science modules can be added at either end to form a mobile train of science instruments.

2. Background

The approach we utilize to develop our reconfigurable robotic explorer is to begin with the basic building blocks of a modular 2-wheeled robotic vehicle called the *Axel2* [1]. An *Axel2* includes a caster wheel attached to an axle by an actuated caster link (Figure 1). This robotic design was developed to address some of the long-term goals for modular and reconfigurable surface explorers. Compared to four- and six-wheel rocker-bogie rovers [2-4], the design for our reconfigurable robotic explorer uses a simpler mechanism to carry out similar maneuvers using less power. Unlike the former rovers, the wheel sizes can vary without having to scale the reconfigurable design. Also, the loose coupling in the multi-*axel* systems reduces the stress on the mobility mechanism, which occurs in rigid vehicles during steering.

Previously, the use of two-wheeled robots has been explored by several researchers at the University of Minnesota [5]. The team has developed small cylindrical explorers (a few centimeters in diameter) that are ejected

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from a cannon mounted on a traditional rover platform. These explorers are controlled by embedded microprocessors and sensors. In addition to exploring surrounding areas (mainly flat terrain), these cylindrical explorers can hop a few centimeters over small barriers. A commercially available robot from Probotics, Inc [6], also uses two-wheeled locomotion. In contrast with these two-wheeled systems, our *Axels* have a unique castor link, are an order of magnitude larger, and are designed for rough terrain exploration. The *Axels* use stereo vision for obstacle detection and avoidance, and are designed to interface with science modules to create extendible explorer configurations.

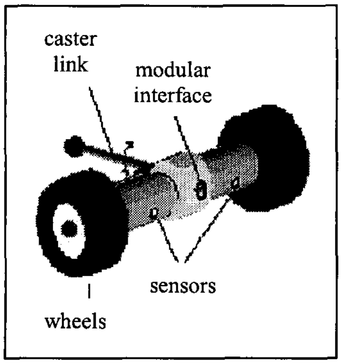

Figure 1. *Axel2* reconfigurable exploratory vehicle

Several researchers are pursuing a different approach to reconfigurable surface exploration. Their main concept focuses on highly redundant robotic systems using very small and modular components [7-9]. These components can be either all identical or selected from a fixed inventory set. The components can autonomously attach to and detach from each other, creating a large number of potential configurations. In the limit as the components get smaller, the robotic system will resemble moldable "digital clay." In his early work at Stanford University, Yim [10] studied, simulated, and implemented a set of these highly modular systems, which he termed "polypods". In more recent work at XeroxPARC, Yim further improved the design of the small modules [11]. While simulations of this work have been very promising, actual implementations of these systems present serious challenges with today's actuation and sensing technologies. In other work, Dubowsky and colleagues at MIT are studying similar systems with a short-term goal of developing a hybrid system combing traditional rover technologies with these highly modular and reconfigurable components [12]. Unlike Yim's work, which uses identical components, researchers at MIT are using a set of fixed components. They introduce the concept of articulated binary elements (ABE) for actuation to simplify the control of these systems. Other work that focuses on the development of low-level reconfigurable robots includes the work of Sanderson at RPI in which a modular reconfigurable parallel robot was designed [13] and Khosla at CMU, whose team developed the I-Cubes system, a self-reconfigurable system consisting of a collection of independently controlled mechatronic links and passive connection cubes [14].

Previous research at JPL focuses on utilizing kinematic reconfiguration for robots operating on rough-terrain [15]. Developing a methodology for kinematic reconfiguration on a real robot continues with the work of Schenker, et al. [16]. Schenker at JPL, in conjunction with researchers at CMU, MIT, and the U. of Nebraska, is integrating various technologies in virtual prototyping, control, and sensing, for the implementation of highly reconfigurable systems. These efforts have taken a different approach to modular reconfigurable design and focus on real-time reconfigurable control to alter the robotic vehicle's geometry in response to changes in the terrain conditions.

3. The Reconfigurable Exploratory Vehicle

The approach we utilize to develop our reconfigurable robotic explorer is to begin with the basic building blocks of a modular 2-wheeled robotic vehicle called the *Axel2*[1]. Its symmetric design enables it to operate in any stable state (e.g. right side up or upside down). This increases its robustness in traversing unknown terrain and in recovering from unexpected drops off small cliffs. Each of the two large wheels is controlled by a separate servo-actuator. A third servo actuator controls the motion of a link carrying a passive castor wheel. The caster link provides an additional applied force for increasing traversal capability over large rocks and in rough terrain. The rotational motion of the caster link is also used to control vehicle tilt, such that embedded sensors can be commanded to point in any direction. By coordinating the motion of the drive wheels and the castor link, the *Axel2* can either move or rotate its body. When both wheels are driven in the same direction, the *Axel2* will move forward. To steer the Axel2, differential control of the wheels is used.

Contained within the axle of the robotic vehicle are different functional devices - a PC104 processing stack, the three actuators, and the mechanisms necessary for driving the main wheels and the caster link. The axle also houses a stereo camera pair of sensors used to determine

[1] To provide clarification, the *Axeln* denotes a reconfigurable robot having *n* main wheels

navigational direction, extract necessary science, and assist in docking maneuvers. Rechargeable batteries are placed at the boundaries of the axle in order to offset the weight felt along the axle length.

As an individual module, the *Axel*2 functions as a simple modular robotic vehicle with simple sensing capability. It can traverse rocks over half its wheel diameter and perform vision-based operations during autonomous exploration. When additional capabilities are required, individual modules are linked together to form a more complex entity. To promote this reconfiguration process, each *Axel*2 is designed with a module interface that allows multiple *Axel*2s to be combined with intelligent instrument modules (Figure 2). This electromechanical module interface is centered on the midsection of the axle. The *Axel2* carries the female parts of the mating mechanism while the science module carries the male parts. The coupling between the *Axel2* and the science module uses a conical surface that corrects for small misalignment (necessary for autonomous attaching).

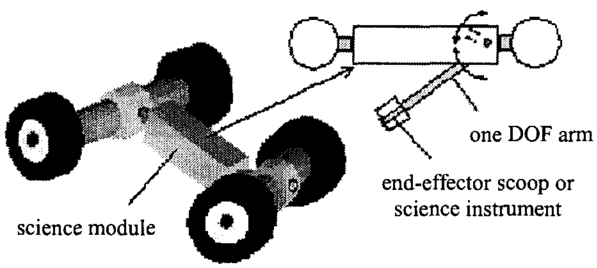

Figure 2. Combining two *Axel*2s with an intelligent instrument module to increase functionality.

The intelligent instrument module provides additional task functionality for the reconfigurable robot. It is defined as any enhancing apparatus, such as a manipulator arm, spectrometer, camera, etc. that allows for task fulfillment. Unlike *Axel2s*, which are all identical, the science modules have different designs to support their science instruments. The science modules are responsible for supplying the actuation/sensing package necessary for the proper positioning and operation of its instruments. Each instrument module contains additional computational power that allows processing of input data, control of mechanical devices, and enables close interaction with the environment. The module interface, which contains electrical and mechanical connections, allows succinct mating of these instrument modules with *Axel*2s and provides direct communication between modules via a serial connection.

Since many challenges still exist with sensing and perception for planetary surface robotics [17], we will present the design of a simple science module to demonstrate the concepts of interfacing with the *Axel*2. This allows us to address the three following areas: (i) a demonstration of the attaching capabilities of modules, (ii) the development of the hardware and software architectures for hot swamping and functional operation, and (iii) the distributed motion control for the reconfigurable robot vehicle, without dealing with the difficulty imposed with high-risk approaches to sensing.

4. Software control for Axel2

To enable self-diagnosis and automatic reconfiguration of modular hardware components, *Axel*n is coupled with a software architecture that provides for autonomous adaptation to hardware reconfiguration. The reconfigurable software architecture [18] consists of simple, general, reusable code development and enables robust and reliable operation during task execution. Specifically, the self-reconfigurable software architecture enables *Axel*n to determine when *physical reconfiguration* is necessary (e.g., in response to task requirements or hardware failure), controls such reconfigurations, and performs *software self-reconfiguration* to conform to the resultant new hardware configurations.

The reconfigurable modular robotic explorer allows a long-term presence to exist on remote planets by providing the capability to repair/replace/reconfigure modules to cope with unexpected events while maintaining accomplishment of functional goals. Since modules, which may be *Axel*2s, effectors, or science instruments, are combined as necessary to meet science goals and mobility requirements, the corresponding software must be capable of enabling this technology. An example of a robotic explorer reconfiguration might involve two *Axel*2 modules docking to each side of a science module in order to perform experiments at a science site, then exchanging the science module with a manipulator arm in order to perform a coring task. Another reconfiguration opportunity may occur in response to terrain traversal difficulties (e.g., adding a "tether" module for cliff descent) or for replacement of a failed mobility or science module that was discovered during task execution.

The ability to autonomously reconfigure the robotic hardware components depends heavily on the supporting software. One of the goals of the *Axel*n system is to increase system simplicity and component generality through modularity. The reconfigurable software architecture mirrors this framework by providing a system in which, as *Axel*n hardware-modules are dynamically docked together or disconnected, their associated software modules employ the same capability.

The reconfigurable software architecture (Figure 3) blends state-of-the-art techniques of distributed robotic control systems, intelligent environmental sensing, and self-reconfiguration to support hardware configuration and task constraints. Task constraints and environmental sensing are used to determine mobility needs and enable software pertaining to appropriate hardware modules to drive the initial hardware configuration process; software will then reconfigure itself for task performance and in response to task needs, occurrence of unexpected situations, or detection of hardware failures.

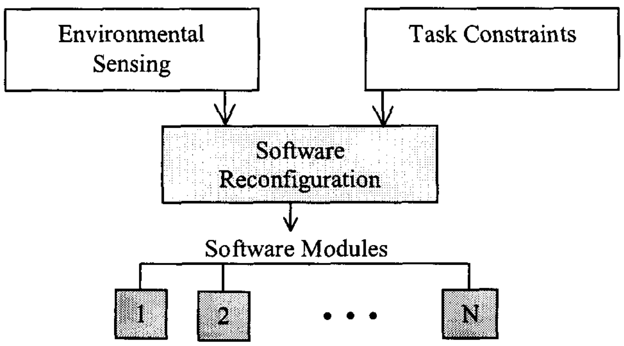

Figure 3: Reconfigurable software architecture

The reconfigurable software architecture involves linking together reusable software modules through connections with other software modules or through connections with external resources, such as science instruments, effectors, or *Axel*n wheel motors. Resource connections are external to the software modules and allow for communication and connection with the physical environment. This allows software modules to receive, as input, data from sensor devices, as well as transmit commands to hardware components, such as wheel motors. A software module can have an unlimited number of incoming and outgoing connections. When data arrives at a module, either from another module or from external sensors, the data is propagated along that module's outgoing connections. In order to achieve various forms of functionality, data flow can be modified through suppressive, inhibitory, or overriding behavior. Software modules are thus easily reconfigurable and interactions with connections between modules can be modified dynamically. The reusable software modules have many different levels of functionality. At one level, basic software modules are constructed to enable different forms of rover mobility as dictated by an *Axel*2 versus an *Axel*4 robotic explorer. At another level, software modules exist that take as input imagery data and determine the number of modules necessary to construct an *Axel*n to enable descent over a steep cliff. These reusable software modules are designed to enable various levels of robotic control such that fundamental functionality can be achieved.

5. Implementation

The *Axel2* robot is a two-wheeled robotic vehicle capable of reconfiguring into a multi-wheeled robotic vehicle of length *n*. Figure 4 shows a close-up of the actual vehicle designed and developed as an *Axel2*. To test the capability of the robotic exploratory vehicle, we demonstrate hardware reconfiguration of an *Axel2* robot to an *Axel4* robot using vision-based docking, and validate the software reconfiguration process through dynamic modification of the explorer's mobility pattern based on changes in the hardware configuration. Vision-based docking involves the process of *Axel*2 identifying the interface module located on the science module, approaching the docking connector, and mating. Figure 5 displays a close-up of the docking connector while Figure 6 give a graphical depiction of the process. A simple science module is shown to demonstrate the concepts of interfacing with the *Axel*2. In this series of tests, we were able to demonstrate the attaching capabilities of the modules, hot swamping and functional operation of the hardware and software architectures, and navigation control of the reconfigurable robot vehicle.

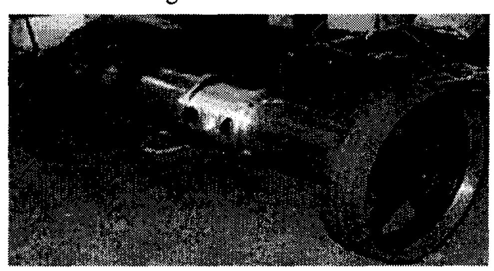

Figure 4. *Axel2* reconfigurable robotic explorer

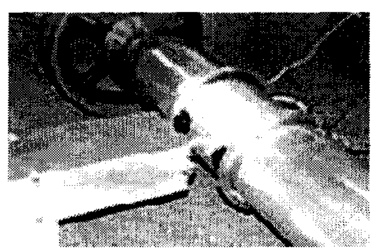

Figure 5. *Axel2* docking maneuver

The reconfigurable software architecture was first tested in adapting the navigation capability of the Axel2. This consists of autonomously determining the best mode of navigation operation depending on the hardware configuration (Axel2 vs. Axel4). This allows the same software architecture to reside on individual Axel2 systems, and yet control the mobility of the Axel4. For implementation purposes, the software was tasked to recognize current robot configuration and differences in hardware, and run different navigation schemes autonomously. The navigation scheme for an Axel2 consisted of driving the wheels either forward, or backward. Once mating occurred, such that an *Axel*4 is constructed, the software reconfigures the robot vehicle's mobility pattern by autonomously selecting a "front" for instantiating the steering and navigation control process (Figure 7).

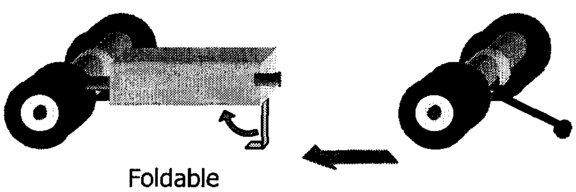

Figure 6. Process of reconfiguring *Axel*2 to *Axel*4

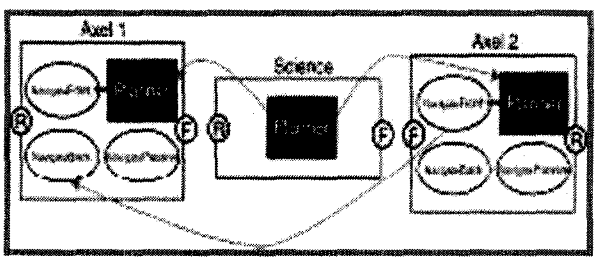

Figure 7. Software reconfiguration of navigation capability

In our tests, we were able to successfully show autonomous reconfiguration of the software and hardware structure. Tests were also run to show the capability of the Axel2 to successfully climb over rocks of half a wheel diameter in height.

6. Conclusion

The ability of the *Axel* explorers to change their mobility systems to adapt to the terrain difficulty is an important capability in surface exploration. The robotic explorer design allows for robust multi-task implementation for operation in natural terrain. The advantage of our approach focuses on the development of both modular hardware and software components to enable reliable functionality. These vehicles can be integrated in a wide variety of robotic applications – from exploration of remote unknown environments to autonomous scouting for victims of natural hazards on Earth. Future work will focus on enhancing the science module capability and performing extensive tests of task operations in hazardous terrain.

References

1. I. Nesnas, "Reconfigurable Exploratory Robotic Vehicles," NASA Tech Briefs, pp. 56, Jul 2001.
2. D. Bickler, "A family of planetary vehicles," Proc. of the Intern. Symp. on Mission Technologies and Design of Planetary Mobile Vehicles, France, 1992.
3. P. S. Schenker, et al., "New Planetary Rovers for Long-range Mars Science and Sample Return," Proc. Intelligent Robots and Computer Vision XVI, pp. 2–15, Boston, MA, Oct. 1998.
4. R. Volpe, J. Balaram, T. Ohm, and R. Ivlev, "Rocky 7: a net generation rover prototype," Journal of Advanced Robotics, 11(4) December, 1997.
5. Paul E. Rybski, et al., "A Team of Robotic Agents for Surveillance", Agents 2000, Spain, June 2000.
6. Probotics, Inc., "Cye-RS" personal robot, http://www.personalrobots.com.
7. I.M. Chen and J.W. Burdick, "Enumerating the non-isomorphic assembly configurations of a modular robotic system," Int. J. of Robotics Research, vol. 17, no. 7, pp. 702-719, 1998.
8. G. Chirikjian, A. Pamecha, I. Ebert-Uphoff, "Evaluating Efficiency of Self-Reconfiguration in a Class of Modular Robots," Journal of Robotic Systems, pp317-338, Vol.13, No.5, 1996.
9. C. Leger. "Automated Synthesis and Optimization of Robot Configurations: An Evolutionary Approach," Ph. D. Thesis, The Robotics Institute, Carnegie Mellon University, December 1999.
10. M. Yim, "Locomotion with a unit modular reconfigurable robot," Ph.D. dissertation, Dept. of Mechanical Engineering, Stanford University, 1994.
11. M. Yim, D.G. Duff, K.D. Roufas, L. Kissner, "Polybot: Demonstrations of a modular reconfigurable robot," Video Proc. IEEE Int'l Conf. on Robotics and Automation, 2000. http://www.parc.xerox.com/ spl/members/yim/modrobots.html
12. S. Farritor, S. Dubowsky, N. Rutman, J. Cole, "A system level modular design approach to field

robotics," 1996 IEEE Intern. Conf. on Robotics and Automation, Minneapolis, pp 2890-5.
13. A. C. Sanderson, TETROBOT: A Modular Approach to Reconfigurable Parallel Robotics, Kluwer Academic Press, 1997;
14. C. Unsal, H. Kiliccote, P. K. Khosla, "I(CES)-Cubes: A modular self-reconfigurable bipartite robotic system," Proc. Sensor Fusion and Decentralized Control in Robotic Systems II, Boston, MA, pp. 2-8, Sep. 19-22, 1999.
15. S. Sreenivasan, B. Wilcox, "Stability and traction control of an actively actuated micro-rover," Journal of Robotic Systems, 11(6), pp. 487-502, 1994
16. P. S. Schenker, et al., "Reconfigurable robots for all terrain exploration," Proc. Sensor Fusion and Decentralized Control in Robotic Systems III, 15 pp., Boston, MA, Nov. 5-8, 2000
17. E. Tunstel, A. Howard, "Sensing and Perception Challenges in Planetary Surface Robotics," IEEE Sensors, Orlando, FL., June 2002.
18. B. Werger, "Ayllu: Distributed Port-Arbitrated Behavior-Based Control," Distributed Autonomous Robotic Systems 4, Lynne E. Parker, George Bekey, and Jacob Barhen (eds.), Springer, 2000:25-34.