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Robonaut 2 – The First Humanoid Robot in Space

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Abstract—**NASA and General Motors have developed the second generation Robonaut, Robonaut 2 or R2, and it is scheduled to arrive on the International Space Station in early 2011 and undergo initial testing by mid-year. This state of the art, dexterous, anthropomorphic robotic torso has significant technical improvements over its predecessor making it a far more valuable tool for astronauts. Upgrades include: increased force sensing, greater range of motion, higher bandwidth, and improved dexterity. R2's integrated mechatronic design results in a more compact and robust distributed control system with a fraction of the wiring of the original Robonaut. Modularity is prevalent throughout the hardware and software along with innovative and layered approaches for sensing and control. The most important aspects of the Robonaut philosophy are clearly present in this latest model's ability to allow comfortable human interaction and in its design to perform significant work using the same hardware and interfaces used by people. The following describes the mechanisms, integrated electronics, control strategies, and user interface that make R2 a promising addition to the Space Station and other environments where humanoid robots can assist people.**

I. Introduction

NASA and General Motors have a long history of working together, taking on formidable challenges, that dates back to their collaboration on the Apollo Lunar Rover. These two organizations have come together again, this time to address the new challenge of developing robot assistants that can work in close proximity to humans.

General Motors has been a leader in the application and development of robotic technology since its initial collaboration with Joseph Engelberger in 1961. That year, GM became the first manufacturer to use industrial robots with its application of Unimate robots in an assembly plant. Today, General Motors employs over 25,000 robots in its Manufacturing Operations worldwide and has influenced the industry over the years by leading technical development efforts in servo electric welding robots, paint application robots, the Unimate PUMA robot for light assembly, and fixturing robots.

Although performance, capability, and reliability have all greatly improved since the first introduction of robots in GM manufacturing facilities, many of the applications targeted for robot use remain the same. Current industrial robots operate in highly structured task environments and are designed and programmed to work in enclosed workcells.

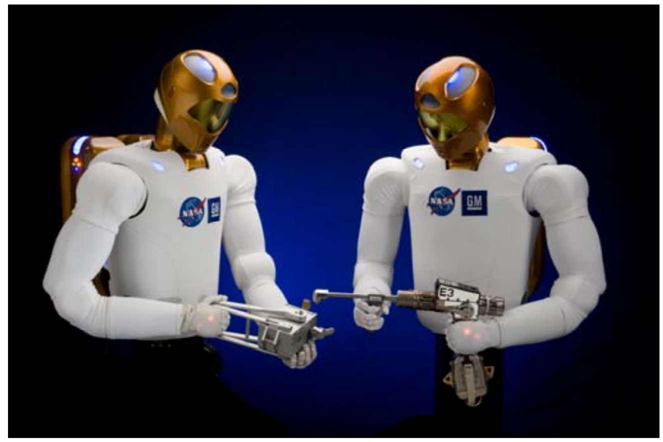

Fig. 1: Robonaut 2 units A and B

The consistency of the task structure enables robots to safely perform their tasks but this same structure also limits task flexibility. While there has been some progress that enables robots to operate in manufacturing environments with less structure, the full technical capability is still not mature and has not been realized. This "capability gap" has limited the use of robots in applications that provide, or require, less structure.

NASA experiences a very similar robotics "capability gap." While many of the maintenance tasks on the International Space Station have been specifically structured to be robotically compatible, the challenge is to increase the breadth of the less well-defined Extra-Vehicular Activity (EVA) tasks that robots can perform. Another manipulator, DEXTRE by the Canadian Space Agency, currently operates on board the station as a robotic servicer. This manipulator, however, utilizes different approach corridors than the human astronauts and relies on specialized interfaces designed for robotic compatibility. Designing additional structure into worksites and interfaces for robotic systems has been successful thus far in space missions but can only addresses a portion of the servicing requirements. Astronauts working with EVA compatible tools still perform a considerable amount of on-orbit maintenance activities.

NASA developed Robonaut 1 (R1) to assist the crew with servicing tasks and to begin to reduce this "capability gap" [1]. R1 has demonstrated, in high fidelity ground based testing, its ability to work with existing EVA tools and interfaces. Anthropomorphic robots, like R1, are well suited for applications in less structured, human environments and they are fully expected to reduce the work load on EVA crew members by performing routine maintenance, assisting the crew before, during, and after EVA, and serving in a rapid response capacity.

NASA's success in developing and demonstrating R1's capabilities attracted the attention of General Motors. GM approached NASA in 2006 as part of a worldwide review of humanoid robotics, searching for new technologies that would help their skilled workforce improve product quality and manufacturing assembly processes. NASA's expertise in systems specifically designed to assist astronauts and GM's desire for safe and flexible robots made the two organizations ideal partners with a shared vision of the enormous benefits to be gained from a robust, anthropomorphic robotic system that can relieve humans, be they factory workers or astronauts, from dangerous, ergonomically stressful, or difficult activities.

NASA and GM are not alone in this vision and in addition to R1, many anthropomorphic robotic systems being developed around the world show that this technology is within reach. Impressive legged humanoids have shown that robots can move about in unstructured environments [2][3]. Robots with multi-degree-of-freedom hands are able to interact with a wide array of objects [4][5] and humanoids with highly dexterous upper bodies have demonstrated the manipulation of everyday objects designed for humans [6].

To achieve the desired performance improvements and the resulting benefits in a next generation humanoid, Robonaut 2 (R2) required a number of significant advancements over its predecessor's electromechanical design, sensing integration, controls strategy, and user interface. At the heart of these advancements are technologies and approaches that allow for increased speed, strength, and dexterity while not sacrificing, and in fact improving upon, a system design that is compatible with direct human interaction.

II. Mechatronic Design

With 42 independent degrees-of-freedom (DOF's) and over 350 sensors, Robonaut 2, shown in Fig. 1, is an impressive example of mechatronic integration. Encompassing two 7-DOF arms, two 12-DOF hands, a 3-DOF neck and a single DOF waist, the system includes 50 actuators with collocated, low-level joint controllers embedded throughout. The system also integrates built-in computing and power conversion inside its backpack and torso.

Prior experience with Robonaut 1 and other robots developed at NASA demonstrated a direct correlation between the overall wire count in a robotic system and the reliability of said system. Thus, the avionic architecture for Robonaut 2 was designed around one central theme – the reduction of conductor count, specifically of those that cross degrees-of-freedom. Focusing on this point is the key to integrating the actuator and sensor dense subsystems of Robonaut 2 into a reliable and robust humanoid.

In order to achieve this goal, a new communication scheme was required. Whereas R1 relied on a point to point RS-485 communication architecture requiring over 100 conductors in each main arm cable, Robonaut 2 has a distributed processing architecture that utilizes a high speed serial communication network. This custom protocol implemented on a Multi-drop Low Voltage Differential Signal (MLVDS) physical layer achieves bus speeds of 50 Mbit/s. When coupled with the robot's bussed power configuration this architecture limits each arm's main bus cable to only 16 conductors. This manageable number is run through each joint, internal to the arm, protecting the cable from inadvertent damage and the environment.

Fig. 2: Custom torsion springs from the R2 series elastic actuators

A. Arms

Robonaut 2, like its predecessor, uses brushless DC motors, harmonic drive gear reductions, and electromagnetic failsafe brakes as the building blocks for the power and torque dense actuators in the robot's human-scale, 5 degree-of-freedom upper arms. The use of series elastic actuation, however, differentiates R2 from previous designs. Developed initially with legged robots in mind, series elastic actuators (SEA's) have been shown to provide improved shock tolerance, beneficial energy storage capacity, and a means for accurate and stable force control [7]. Not surprisingly, these features are of interest to the manipulation community as well, where humanoid robot arms have also been designed with passive compliance in their actuation [8]. Robonaut 2's series elastic arms do not sacrifice strength, or payload capacity, to achieve fine torque sensing at each of its joints. This is made possible by the custom planar torsion springs that are integrated into each arm actuator and the two 19 bit absolute angular position sensors that measure each spring's deflection. Shown in Fig. 2, these springs are uniquely sized for each arm joint and are capable of elastic deformation across the full range of their actuators' continuous torques. This gives Robonaut 2 the fine force resolution to implement a variety of impedance control objectives while still enabling the robot to handle significant human-scale payloads, as seen in Fig. 3.

Fig. 3: Robonaut 2 lifting 20 lbs at full extension

To achieve R2's strength, its arm speeds of over 2 m/s, and the data processing required for the robot's many sensors and control modes, a considerable amount of capability has been distributed to the low level joint controllers embedded in each of the arm joints. These highly integrated controllers, termed Superdrivers, serve as the workhorse of the upper arm motion control strategy. They consist of an FPGA based controller with an embedded PowerPC processor and programmable logic that is coupled with a 3 phase brushless DC inverter bridge. The Superdriver performs motor commutation and current control, serialization and de-serialization of joint data and commands, sensor processing, and control of the arm's series elastic actuators. The embedded processor runs these control loops at 10KHz while the programmable logic is used for the MLVDS communication scheme and motor commutation, which can be either six-step or space vector. Additionally, the SEA control loop can be configured locally to accept either position or torque commands.

Because they are collocated with each actuator, the Superdrivers provide a streamlined and reliable means of interfacing with all of the analog and digital sensors at each joint. These measurements include readings of the three motor phase currents, the motor bus current, joint temperatures, incremental motor position, and the two absolute position sensors integrated in each SEA to provide both spring deflection and output joint position.

Every Superdriver printed circuit board is integrated into the overall upper-arm joint design in a true mechatronic sense. Each board plugs into its corresponding joint with two blind mate connectors to provide a clean and robust interface that prevents stress on any of the joint wiring, limiting life and fatigue related failures, while also allowing for easy access for routine upgrades, maintenance, or repairs.

B. Hands

The Robonaut 2 hand and forearm, shown in Fig. 4, are designed to improve upon the approximation of human hand capabilities achieved by its predecessor, Robonaut 1 [9]. The five fingered, 12 DOF hand and the forearm, which houses two wrist degrees-of-freedom, form a completely self-contained unit. The 18 motors and 8 circuit boards required for these 14 DOF's are packaged inside the forearm and only power and communication from the upper-arm is needed. This makes the Robonaut 2 hand both an important subsystem of the full humanoid robot and a modular, extremely dexterous, stand alone end-effector in its own right. The R2 hand has the capability to manipulate a large set of EVA tools, conventional hand tools, and soft goods.

As seen in Fig. 5, the fingers are divided into a dexterous set used for manipulation and a grasping set used to maintain stable grasps while working with large tools. The dexterous set consists of two, three DOF fingers (the index and middle) and a four-DOF opposable thumb. The grasping set consists of two, one DOF fingers (the ring and little finger). All fingers are shock-mounted within the palm, giving the hand rugged grasping options.

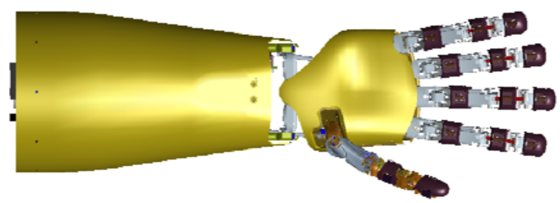

Fig. 4: CAD model of the Robonaut 2 hand and forearm

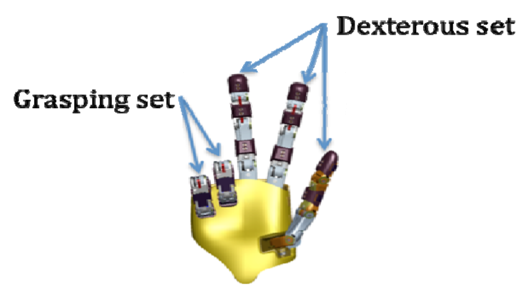

Fig. 5: Robonaut 2 finger groupings

The performance of the Robonaut 2 hand is measured by its ability to emulate Cutkosky's grasp taxonomy [10]. While the Robonaut 1 hand could only emulate about 50% of these grasps, improvements made in the Robonaut 2 hand allow for successful grasps across 90% of the taxonomy. Fig. 6 shows the Robonaut 2 hand in the Cutkosky grasps. The increase in capability of the hand comes primarily from advancements made in the thumb design. The four DOF R2 thumb, optimized to achieve a very human kinematic layout, is the same scale as a human thumb. The design also provides the thumb with significantly greater strength than the opposing fingers.

With the actuators remotely packaged in the forearm, the fingers are driven by a tendon-conduit transmission. Each of the dexterous fingers, with n DOF's, is driven by n+1 tendons in a coupled configuration that allows for this

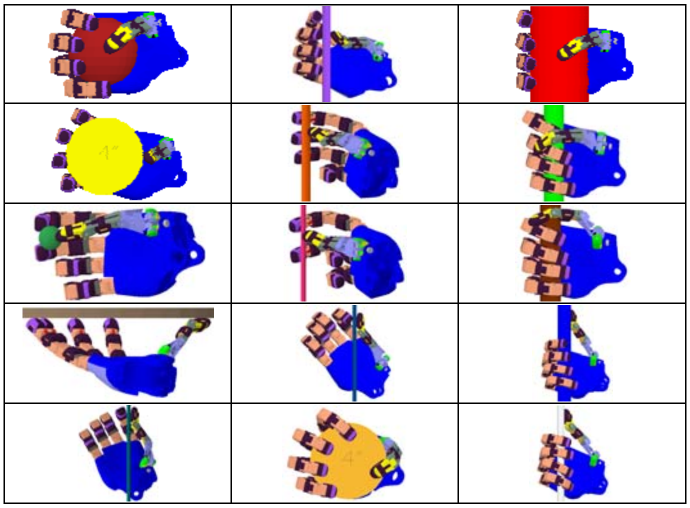

Fig. 6: Robonaut 2's emulation of Cutkosky's Grasp Taxonomy

minimal set of actuators [11]. Tension sensors for each tendon are embedded in the palm. These sensors allow for the force control of the fingers, given the redundant network of tendons. In addition, each finger phalange is designed to mount a custom six-axis load cell [12], for a total of 14 in the hand. These sensors provide all six axes of force and moment, allowing for measurement of external contact forces as well as shear force and slippage of objects held by R2.

Continuing the theme of minimal wire count, only 6 conductors, housed in a single connector, pass from the upper arm to the power and data distribution and processing electronics of the forearm. Once inside the forearm, there are two different types of control boards. At the top level is a single forearm controller that communicates via MLVDS with the robot's central IO processor and serves as a supervisor and controller over six motor controller boards. These motor controller boards each interface to and drive three of the lower arm's 18 motors. They are equipped with phase current sensing and the ability to set continuous current limits to protect against excessive force or thermal load on the actuators.

III. Control Strategy

A. Implementation

The control software for Robonaut 2 is a multi-threaded application spread across two PowerPC processors in a Compact PCI chassis. The application code developed in ControlShell[R] runs on the VxWorks[R] operating system. The first processor handles the collection and high-level processing of sensor information from the embedded joint controller network. It also oversees an extensive safety system evaluating the kinematics and force levels in the system. The second processor implements the desired control law and computes the robot's kinematics. Sensor data and computed quantities are shared between the two processors via a shared memory region through the PCI backplane. The central processors pass down desired joint commands to the Superdrivers and the forearm controller where the embedded processors implement the aforementioned 10 kHz torque or position control loops.

B. Architecture

The Robonaut 2 controls architecture provides an impedance based control system with great flexibility. The concept of impedance control provides for robust interaction with the environment, while allowing for both motion and force control objectives [13]. The architecture implemented in R2 allows for multiple, prioritized tasks that can control the robot with respect to different spaces and different nodes of interest in the kinematic tree. At the heart of this framework is an impedance law with two hierarchical relations: an operational-space impedance as the top priority and a joint-space impedance as a second priority. Multiple such laws can be implemented hierarchically.

The primary operational space relation can be defined with respect to any of a number of possible nodes in the kinematic tree, and it can be defined with respect to the linear and/or angular motion. Given the task definition, the relevant kinematics are generated in real-time for all joints upstream of the selected node in the kinematic chain. The waist joint can be optionally included in the kinematic chain, allowing the arms to be controlled either independently or integrated for whole-body motion. In addition, a PID force control objective can preempt the primary operational space relation to create a hybrid force/impedance control behavior in the operational space.

The secondary joint-space impedance relation governs the joint motion lying in the null-space of the primary task, including the joints downstream of the selected node. It can also serve as the primary task and fully govern all arm joints.

The net effect of this architecture is to provide a system that can handle diverse assembly tasks while interacting robustly with the environment. Different force or position objectives can be commanded to the robot with respect to different points on its arm, while the redundant DOF's can be commanded to maximize range or avoid obstacles.

C. Arm Control Law

The dual-priority control described in the previous subsection is defined as follows. First, consider the equations of motion for the full system of manipulators.

$$M\ddot{q} + c + g - \tau_e = \tau \quad (1)$$

M is the joint-space inertia matrix, q is the column matrix of joint angles, c is the column matrix of Coriolis and centripetal generalized forces, g is the column matrix of gravitational generalized forces, and τ and τ_e are the column matrices of actuated and external torques, respectively.

Second, consider the desired closed-loop impedance relations for both the operational and joint spaces.

$$\begin{aligned} M_o\ddot{x} + B_o\dot{x} + K_o\Delta x &= F_e \\ M_j\ddot{q} + B_j\dot{q} + K_j\Delta q &= \tau_e \end{aligned} \tag{2}$$

M_o, B_o, and K_o represent the desired operational-space inertia, damping, and stiffness matrices, respectively. M_j, B_j, and K_j represent the desired joint-space inertia, damping, and stiffness matrices, respectively. x and F_e represent the operational-space coordinates and corresponding external forces, respectively, and the Δ indicates the error in the respective variable with respect to its desired value.

To eliminate the need for sensing external torques, the impedance inertias are set to the passive inertia of the system: $M_o = M$, $M_j^{-1} = JM^{-1}J^T$. The full solution for this dual-priority impedance control law is presented in [14]. For the sake of the implementation, the following approximation is employed in R2 to eliminate the need for the inertia matrix.

$$\begin{aligned} \tau &= -J^T\left(B_o\dot{x} + K_o\Delta x\right) - N\left(B_j\dot{q} + K_j\Delta q\right) + g \\ N &= I - J^+J \end{aligned} \tag{3}$$

J is the Jacobian matrix mapping joint velocities to operational-space velocities and N is the null-space projection matrix for J.

A closed-loop analysis shows that this control law provides the desired joint-space impedance relation (2) projected into the null-space; in the range-space, it provides the desired operational-space impedance relation (2) with a disturbance from the null-space dynamics. The effects of this disturbance, as well as the effects of neglecting the Coriolis forces and the derivative of J, are negligible for R2's range of speeds.

A similar relationship to (3) is used for the hybrid force/impedance mode. A null-space projection matrix for the force task Jacobian is used to project the primary and secondary tasks into the force task's null-space.

D. Finger Control Law

Since the fingers are actuated by coupled tendons, rather than independent drives, a special control law is needed. It turns out that the existing control laws for tendon-driven manipulators that employ tension feedback all actually control the manipulators in the tendon-space. These laws demonstrate a first-order coupled disturbance between the joints. Alternatively, the control law can be formulated in the *joint-space* to eliminate this coupled disturbance and increase the speed of the response. A full discussion is available in [15]. The final control law presented here for the actuators implements an inner position control loop:

$$p_c = p - k_d\dot{p} + \begin{bmatrix} R \\ W \end{bmatrix}^T K_p\Delta\begin{pmatrix} \tau \\ t \end{pmatrix}, \tag{4}$$

p and p_c represent the actual and commanded positions for the actuators, R ($n \times n+1$) represents the kinematic mapping from tendon tensions (f) to joint torques, W is a row matrix selected orthogonal to R, t is a scalar measure of the internal tension on the tendon network ($t = Wf$), and K_p and k_d are constant gains.

IV. Working in Proximity to Humans

Both industrial manipulators and R1 utilize kill switches or emergency stop buttons as part of their standard safety systems. In the case of an industrial manipulator, additional safety devices such as light curtains or sensor mats also provide power cutoffs in the event a human enters the robot's workspace. R2 has moved away from this paradigm. The impedance control strategy noted above limits the force that the robot applies to the environment. This ensures that when inadvertent human contact occurs, the resulting force felt by the person is comfortable and the robot can be easily restricted by just manually pushing its limb out of the way.

In parallel to R2's torque control are software monitoring routines that use multiple force sensors in the robot's arms in addition to the arm and waist joints' torque sensing to independently monitor the robot's forces. If a predefined limit is exceeded at either the joint or the arm level, the robot disengages motor power and stops. An array of additional software routines on several processors continuously checks the health and communication status of the two main force/torque monitoring loops. The result of this architecture is a triple redundant system to keep forces within allowable limits that has been approved to fly on the International Space Station without the need for an independent emergency stop button. Thus, what once served as an E-stop during development has been converted to a simple motion-stop, or M-stop. The robot operator has the discretion to use the M-stop as a convenience while running the robot, but crewmembers are allowed into the robot's workspace without having to use it.

V. User Interface

One of the unique challenges of working with R2 is distilling the control of a complicated system into a user-friendly design. R1's telepresence control system [1] is easy to use, and definitely has a role, but it is best complimented by a higher-level interface. In industrial and commercial environments, suppliers have created interfaces to move, monitor, and manage standard robotic arms. Unfortunately, no commercial supplier offers a standard interface to control a 42 degree-of-freedom humanoid robot.

The custom R2 interface uses common elements such as buttons and sliders to provide the user with direct control over the basic functionality of the robot. These objects are organized by function and presented to the user based on the pre-determined needs of a variety of tasks. This simple interface enables novice users to perform basic tasks on the robot without requiring excessive training.

The interface uses a monitored network link to receive

Fig. 7: Robonaut 2 User Interface

telemetry, events, and status updates from the system and to send commands out to the robot. The data is displayed on the screen using information rich symbols and controls and the user interface modifies the visual appearance of these objects to highlight conditions that require additional attention. These interface features enable the operator to filter the large amount of available data to quickly and easily understand the state of the robot. Additionally, the on screen interface is dynamically configurable to allow the operator to move displays to an orientation well suited for the current task and it provides the ability to log and graph both incoming and outgoing data.

In addition to basic control of the robot using standard input methods, the R2 user interface also provides a custom programming language. This language is designed to work closely with the design methodologies implemented in the robot hardware and control algorithms. It provides a flexible way to integrate sequenced motions with sensor feedback and it allows for the creation of complicated behaviors from an ever-growing library of existing primitives developed for R2. Like the robot's other subsystems in both hardware and software, the user interface aims to make working with Robonaut 2 an easy and comfortable experience.

VI. Activities in Space

Scheduled to arrive on the International Space Station in early 2011, Robonaut 2 will be the first humanoid robot sent into space. Once deployed on the station, R2 will perform a variety of experimental tasks. While working side-by-side with human astronauts, Robonaut 2 will actuate switches, use standard tools, and manipulate soft goods and cables. The results of these experiments will demonstrate the wide range of tasks a dexterous humanoid can perform in space and they will help refine the methodologies used to control dexterous robots both in space and here on earth. As a learning platform, R2 on station will be of immense value to future space robots and humanoids in general.

It is moving beyond initial experiments, however, that is most exciting. As R2's performance is tested on orbit, algorithms and control systems with even more capability can be developed, R2 can become more autonomous, and it can transition from being a valuable tool tested and used by astronauts to a team member serving as a flexible assistant. This is only made possible by the significant advancements made in the Robonaut 2 design ranging from increased speed and dexterity, to improved mechatronic integration and reliability, from robust force sensing and impedance control, to a redundant safety architecture that makes R2 not only work-capable but also appropriate for interaction directly with humans.

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