Towards a Personal Robotics Development Platform: Rationale and Design of an Intrinsically Safe Personal Robot

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***Abstract*—The most critical challenge for Personal Robotics is to manage the issue of human safety and yet provide the physical capability to perform useful work. This paper describes a novel concept for a mobile, 2-armed, 25-degree-of-freedom system with backdrivable joints, low mechanical impedance, and a 5 kg payload per arm. System identification, design safety calculations and performance evaluation studies of the first prototype are included, as well as plans for a future development.**

I. INTRODUCTION

THE focus of the project presented here is to develop robust and safe robots that do real tasks for humans. The many research robots developed in the United States, Europe and Asia can generally be classified into two categories: 1) humanoid robot research platforms that generally focuses on bipedal locomotion or human-robot interaction before manipulation[1,2], resulting in robots that are not designed to demonstrate practical manipulation performance; and 2) robot arm-and-gripper test beds that allow research on manipulating real objects[3]. These research prototypes or modified industrial robots are not consumer-grade, human-safe or robust enough to be considered true development platforms. Our project, similar in spirit to ideas also espoused by others [e.g.,[4]] has concentrated on the design and implementation of a fully integrated development platform that is designed to be safe and capable in human environments and is being set up to be shared with the greater research community (Figure 1).

A. Robot Design Criteria

Successful robot designs result from a tight coupling with the specific application space targeted by the developer. Robots designed, for example, for industry, space, surgery, and rehabilitation have significantly different operational criteria. The application space driving the design of this robot is broadly defined as human scale manipulation tasks in human environments (see section II-A). Achieving functionality and safety in the variety of unstructured environments encountered in this application space presents a challenge since system behavior is dictated by software, not a human operator.

Figure 1: Photo of Personal Robot PR-1 Prototype

Software does not exist yet to perform the decision-making humans do when dealing with safety, though this is an active area of research[5,6,7,8,9,10]. To advance the area of personal robotics, for which assuring human safety is not optional and cannot be handled through software alone, the mechanical design of the robot must be the ultimate safeguard.

B. Safety-Performance Trade-offs

Safety for personal robotics includes both the safety of humans and objects that may be present in the robot's environment as well as the safety of the robot itself. Traditional robot actuation schemes result in a trade-off between capabilities to complete tasks (available forces, controllability) and safety in the face of system or human error.

Robots on the performance end of this tradeoff have large motors and gear reductions in their drivetrains, while robots that prioritize safety have small motors and low, efficient reductions. Traditionally, strong actuation schemes that rely

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on large motors and gear reductions can be controlled with force sensors. However, the intrinsic inertia of such systems limits the degree to which such robot systems can be safely controlled in unstructured environments. Direct-drive or efficient, low-reduction actuator systems can be made more capable by increasing the actuator size. These systems have the advantage of being fundamentally current/torque/force controllable but have the disadvantage of requiring large/heavy/expensive motors and amplifiers while still having the potential to quickly dump huge amounts of energy into the environment[11].

Advanced actuation approaches that overcome this traditional trade-off include micro-macro actuation schemes[12] and series elastic actuation schemes[13]. One drawback of these actuation schemes is that they rely on mechanical sensors for safety. Rather than getting their force control at a fundamental level, the current amplifier, they rely on higher-level control loops closed around mechanical sensors. In addition they limit the types of control schemes that can be applied due to the intrinsic dynamics of the elastic element in the drive train.

This paper presents an actuation scheme that achieves current amplifier based force-controlled manipulation of large payloads using small joint motors (see section II-D).

C. *Regulations and Standards*

Industrial robot safety has been the subject of regulation and standards for decades, but the bottom line is always that humans and robots are to be kept physically separate except in very precisely defined scenarios, such as on-site programming and repair. Although ISO suggests that parts of the current standard, ISO 10218-2006[14], may be useful in non-industrial robotics applications, there are no ISO or other regulations specifically for service, rehabilitation or personal robots. Safety in design is ultimately steered by professional codes of ethics, such as the IEEE code, whose ten rules start with the commitment of its members to "… accept responsibility in making decisions consistent with the safety, health and welfare of the public…" Countries such as Korea[15] are formally beginning to address the issue of regulations and standards in personal robotics.

D. *Personal, Service and Rehabilitation Robotics*

Personal robots are defined only by the use domain: human environments. They must coexist safely with humans. While it is clear how they are different from industrial robots, which are confined to restricted-access areas, the distinction with therapy, service and communication robots is more subtle yet important. Considering only safety criteria, Personal Robots are similar to these other classes; however, functionally, there are major differences. Therapy robots have a very specific physical user interface to people to provide a well-defined and low-degree of freedom (DoF) set of exercises. The MIT-MANUS, for example, has a cuff-interface to a human wrist[16] for planar exercises, and the Hocoma Lokomat® treadmill robot[17] uses cuffs to attach robot arms to human legs in vertical-plane motions. These robots move in well-circumscribed paths and have limited range. The most important safety consideration is that these robots are always used under human (therapist) supervision. They are not multi-purpose, as are assistive, personal robots.

Service robots such as the Roomba®[18] and "Remote Presence"[19] physician robot have no capability to manipulate objects; their safety comes from their inability to exert large manipulation forces. Their functionality comes from their mobility and their internal abilities, in the one case cleaning and the other item transport.

Communication robots (encompassing educational, cognitive-assist and pet robots) are inherently safe since their actions are meant to convey emotions and information not perform tasks[20].

II. THE DESIGN OF PR-1

A. *Design Rationale*

Fundamentally, for a robot to be useful in human environments and perform tasks for people, it needs to have capabilities similar to humans. The following is a subset of the applications for which the research and development using PR-1 is being planned:

- Around the House: doing the dishes, tidying up, handling laundry, cleaning
- Aging Populations: carrying heavy things, remembering where things are, retrieving items, preparing food, cleaning
- Assisting People with Disabilities: telemanipulation, feeding, doing chores, monitoring health and activity
- Operations: Behind-the-counter food service, pick and pack tasks, stocking grocery stores, tracking inventory, retrieving items, maintaining a searchable physical file system.

From our analysis of these applications, a set of minimum capabilities was derived that includes the following:

- Support loads of 50 N (~10 Lbf) with one arm
- Grasp, carry and place a standard brick with one arm
- Use both arms to move a full pot of water from one counter to another
- Open doors, cabinets, drawers with one hand
- Pick up dishes from a table and place them in a dishwasher
- Navigate wheelchair-accessible areas (doors, elevators, ramps, hallways) and handle common obstacles (door thresholds, floor-rug transitions, extension cords).

In addition to constraints imposed by individual tasks the goal of performing these types of tasks drives the following characteristics of the entire system: human safety, robustness and payload.

Human safety: The system must be safe enough to work in human environments around humans. Achieving this level of safety requires both the hardware and software systems to be integrally designed from the beginning of the design process. Mechanical design safety includes minimizing inertia, providing back-drivability, eliminating pinch points, carefully managing kinetic and potential energies as well as force output, and making appropriate materials selection. Software design safety includes layering of code for sensor and actuator fault tolerance, mechanical energy limits and checks to ensure that bugs in high-level code cannot result in unsafe robot performance.

Robustness: In order to develop real world applications for robotics, we believe that, while simulation is a powerful tool for coding high-level software, developers must be able to implement and test their programs on a real robot. To this end the robot needs to be robust. For example, it must be able to gracefully handle unexpected environmental conditions and buggy software commands without any down time. This level of durability can be achieved by designing the mechanical systems to be robust to collisions through mechanical means and by adding a low-level layer of safety code that ensures that commands to the actuators cannot break the robot.

Payload: Up to now, robots have been strong and massive or weak and light, but never strong and light. Payload ratios (payload over manipulator weight) for human-sized industrial robots are on the order of 1:10, compared to a human arm ratio of approximately 1:1. Our system has a human-like payload ratio through an innovative gravity compensation mechanism that reduces structural weight, electric motor mass and torque requirements, while still accommodating heavy loads. The accomplishment of an order of magnitude reduction in structural mass has significant implications on safety, usability, and appropriateness of use in human environments.

B. Overall Configuration

Mobility: While fully holonomic (omni-directional) drivetrains exist, no existing system provides robust performance in real-world situations, i.e., able to move over doorway thresholds, curbs and extension cords. The design of PR-1 couples a 2-DoF differentially-driven base with torso rotation to approximate holonomic motion for the two 7-DoF arms mounted on the upper torso. With this 2-wheeled base, our indoor-environment robot can drive smoothly at speeds up to human walking speed of 2 m/s, bump over 1-2 cm obstacles such as carpeting, thresholds and cords, and allow the arms to be positioned virtually anywhere in a natural human-like configuration.

The base includes two pneumatic-tire wheels with 6 Nm continuous torque to each wheel, enabling a climbing capability of 8°. The base also includes two suspension casters, the batteries, power electronics and chargers. The base and the torso are coupled by a 43 cm vertical leadscrew and a ±60° vertical-axis rotating joint (Figure 2).

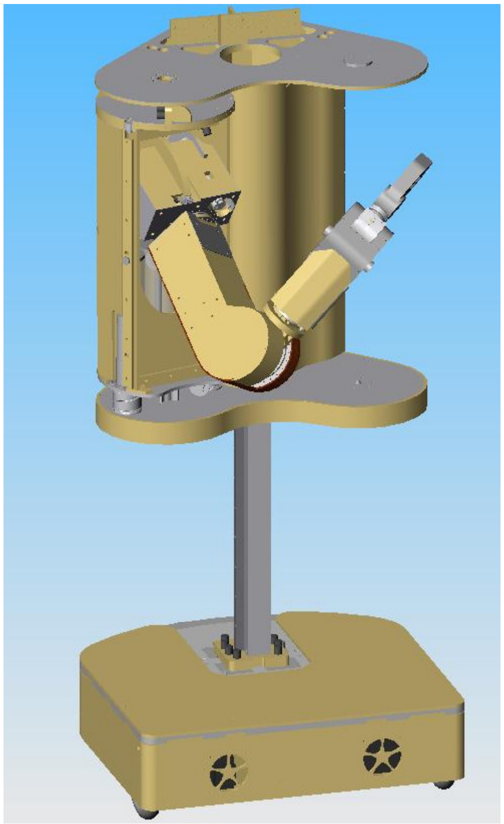

Figure 2: Personal Robot PR-1 (shown with one arm and with torso extended)

Manipulation: To manipulate objects that are common in work and home settings, PR-1 has two arms with ranges of motion and force similar to human arms, each with a simple gripper capable of typical human-like grasps. Designed to avoid pinch points or external wiring, a modular approach makes it possible to add specialized hardware and end-effectors. The two arms are mounted to the torso on ±60° vertical axis joints.

The two 7-DoF arms each have pan and tilt joints, upper arm rotation, elbow flexion, forearm rotation and wrist flexion and rotation (Figure 3). To facilitate 2-armed tasks, the upper arm member is angled inward at the elbow (toward midline with shoulder rotation at mid-range), and the lower-arm segment is angled inward at the wrist when the elbow is in mid-range (Figure 4). The arms have a 5 kg payload each (in addition to the gripper weight) and a dynamic overhead of 15 N. The 3-DoF wrist uses a dual-belt drive and differential gears for pitch and roll motions. A one-motor gripper, built by Otto-Bock Health Care as a human hand prosthesis (Greifer® prosthetic gripper) with quick-release mounting, a continuous rotation wrist roll joint and a 140 N grip capability, allows for hook, pinch and cylindrical prehension of objects, typical of human grasp ability.

C. Low-backlash Drivetrain Design

To achieve low backlash on the joints with less than 360°

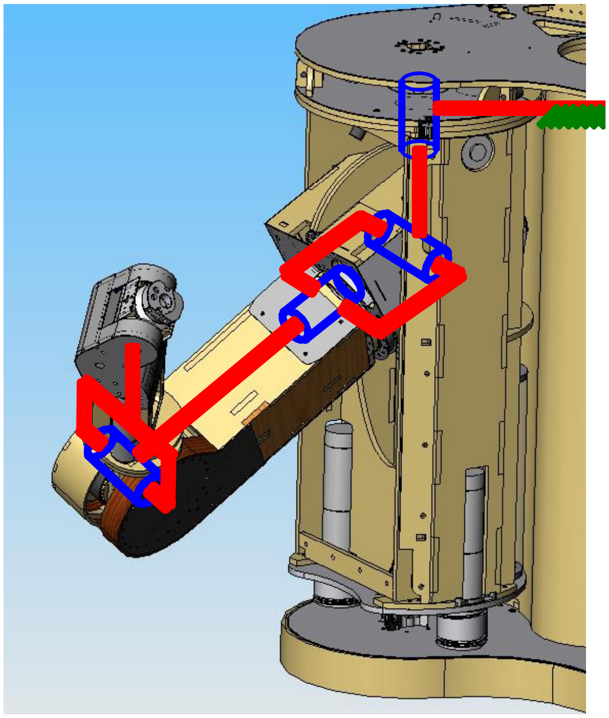

Figure 3: PR-1 arm kinematics.

range-of-motion (i.e., all of the torso and arm axes, and excluding the wheels, vertical lift, wrist and gripper), each drive motor is paired to a backdrivable 4:1 gearhead on which is mounted a toothed pinion. We have coupled this to an innovative, easily-tensioned and inexpensive belt drive. Its drive pulley pinion engages a toothed belt that in addition passes around two idlers to maximize pinion tooth wrap and torque transfer ability. The toothed belt wraps around a sector of the pulley on the driven joint, with the belt then secured and tensioned at two points on the sector.

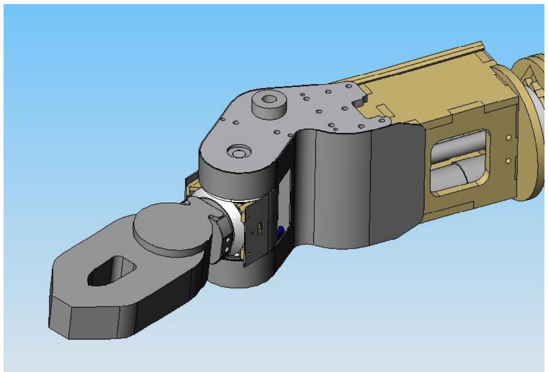

Figure 4: Wrist configuration showing inward angling of pitch-joint.

D. *Novel Arm Actuation System*

The upper and lower arm links of each arm have redundant actuation mechanisms that act in concert to provide both payload capacity and safety in unstructured environments: a gravity compensation system and joint torque actuators.

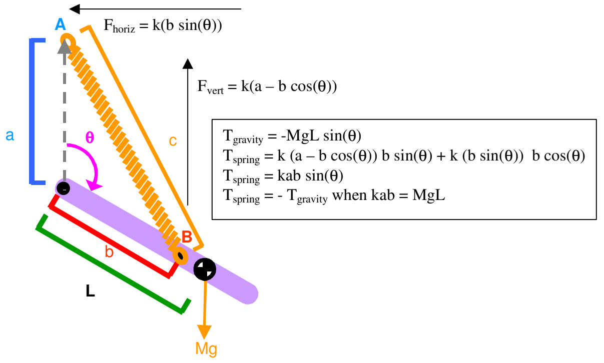

Figure 5a: Gravity compensation principle with derivation.

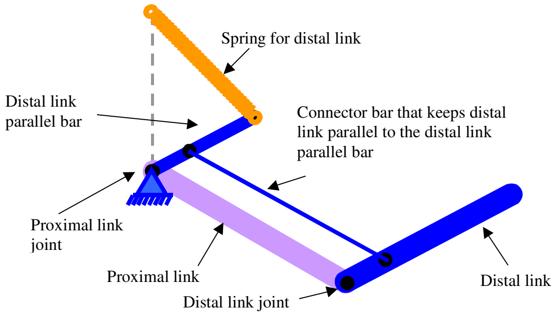

Figure 5b: Parallelogram mechanism to allow compensation needed at the elbow joint (distal) to be attached at the shoulder (proximal), and attached by a cable to the spring-motor components in the arm base.

The gravity compensation system, grounded in the base of the arm, passively floats the arm and payload throughout workspace of the arm. This reduces the need for large joint motors in the arm segments and enables the use of backdrivable transmissions, which is imperative for human and robot safety in unstructured environments. This gravity compensation system uses compression springs, highly-geared, small motors and steel cables mounted to the arm segments in an innovative kinematic arrangement that provides passive gravity compensation throughout all arm configurations with a one degree of freedom payload set point adjustment, similar in concept to other mechanisms in rehabilitation and human service robot designs[21,22,23,24].

The gravity-compensation system uses a geometry-based principle[25] to linearize the force required to counter the angle-dependent effect of gravity of a mass on a rotating joint, as shown in Figure 5a, effectively allowing the arm to passively float throughout its workspace. The system achieves an effect similar to that of a mass counterbalance without the additional inertia, utilizing springs instead of masses to store the required potential energy. Each arm counterbalance mechanism has an additional actuated degree of freedom to adjust for the payload to be counterbalanced.

In addition to the gravity counterbalance system there are motors on all the arm joints for exerting manipulation forces. Because the joint motors do not need to handle gravity loads, they can be low-torque and have small, efficient gear reductions.

To implement the gravity compensation principle in our robot, a cable and set of pulleys are used to allow placement of the springs in a convenient location (the base of the arm). This system can work directly for the shoulder joint. To be able to provide gravity compensation for the forearm link, a parallelogram system (Figure 5b) is used to transfer the force-vectoring load required at the elbow to the more proximal shoulder location, with a second gravity compensation spring then mounted in the base of the arm, alongside the first system for the upper-arm link.

This system achieves 5 kg payload per arm with current amplifier based force control and backdrivable joints while minimizing the effective inertia and maximizing power efficiency.

E. *Power System Architecture and Wiring*

Power electronics and batteries in the base allow for 4 to 8 hours of typical autonomy, depending on the operational situation and tasks being performed. The system can draw 2kW peak power and 1kW continuously. Smart-battery technology allows for computer monitoring of charge state and fast charges from a 110/220VAC electrical outlet.

The computer electronics and all of the motor drives (except those for the wheel-drive motors) are located in the back of the torso.

All wiring is designed to be internal to the robot structure, although the first prototype still contains external loops across the elbow and shoulder joints. The gripper, since it features continuous rotation, has a small multi-slipring connector for motor power and encoder signal transfer.

F. *Controller Architecture*

The software communications architecture is a flexible and extensible system that handles data flow between functional modules. The communications layer handles inter-process communication on one computer and across many computers, enabling the robot to leverage computer resources both on and off the robot. The layer is implemented on different operating systems and programming languages for maximal flexibility.

The current prototype has two computers onboard (Pentium-M small-form-factor computers). One computer handles non real-time functions, and the other computer runs a real-time operating system based on Linux and RTAI and implements a full dynamic model of the robot. This computer communicates in real time with the motor drive stacks over wired Ethernet at a 1 kHz rate for each motor. All motor driver communication and control functionality is implemented in firmware on CPLDs (complex programmed logic devices), which generate the PWM signals, have access to all sensor readings on the board (including sensed motor current), and communicate with the host system.

III. SOFTWARE ARCHITECTURE

A. *High-level Software*

At present, to demonstrate the functionality of the hardware, the robot software supports teleoperation control from a workstation consisting of two SensAble Technologies Phantom® 3.0 input devices and a foot pedal arrangement.

B. *Future Plans for Software Development*

Developed as a personal robotics programming platform, this robot will be the site for extensive further work in all aspects of robotics involving mobile manipulation tasks. The software is currently being extended for use as a software development platform focusing on the technologies required to enable the types of personal robotics applications outlined in section II-A.

IV. SYSTEM IDENTIFICATION AND EVALUATION

Since PR-1 is designed to work in human environments, its specifications are approximately human-like, with some improvements (such as the continuously rotating wrist joint), and some simplifications, such as the use of wheels instead of humanoid legs. The specifications are given in Table 1.

Table 1: Specifications for the 2 arms and body of PR-1 are shown, including ranges of motion, mass properties and link lengths.

Manipulators: 4-DoF Arm + 3-DoF Wrist + 1-DoF Gripper

Force Output/Arm	
Payload	5 Kg (11 Lb)
Force Output*	15 N (3.4 Lbf)
Grip Force	140 N (31 Lbf)
Max Effective Inertia	5 Kg (11 Lb)
Range of Motion	
Shoulder Pan	170°
Shoulder Tilt	90°
Upper Arm Roll	180°
Elbow	140°
Forearm Roll	180°
Wrist Pitch	130°
Wrist Roll	Continuous
Grip	95 mm max
Lengths	
Upper Arm	400 mm
Forearm	321 mm
Wrist to Grip Location	120 to 200 mm

Body: 1-DoF Head + 2-DoF Torso + 2-DoF Wheels

Range of Motion	
Upper Body Vertical	430 mm
Upper Body Rotation	120°
Size	
Shoulder Height - Max	1110 mm
Shoulder Height - Min	680 mm
Shoulder Width	644 mm
Base Width	640 mm
Base Depth	600 mm
Total Mass	98 Kg
Climb Grades up to	8°

* Independent of payload

The Manipulator Safety Index (MSI) developed by Zinn[26] gives an indicator of the likelihood that a manipulator will cause severe injury in the event of contact with a human head. The driving variables are the manipulator's effective inertia, impact velocity, and interface stiffness. For PR-1, these variables were experimentally determined and their realistic ranges are listed in Table 2. The MSI range for PR1 has a very low risk of serious injury compared to industrial robots such as the PUMA-560.

Table 2: Safety calculations for PR-1 (low and high parameter estimates) and the PUMA-560 robot (all without end-effector). The Modified Abbreviated Injury Scale (MAIS) range: 1=minor, 3=severe, 6=fatal injury.

	Effective Inertia	Impact Velocity (m/s)	Interface Stiffness	MSI	Likelihood of MAIS-3 Injury	50% Chance MAIS Level
PR-1 Low Est.	4 Kg	2.5 m/s	1 kN/m	0.2	1%	<<1
PR-1 High Est.	8 Kg	5 m/s	15 kN/m	44	5%	<1
Puma	20 Kg	10 m/s	100 kN/m	1800	60%	4

V. DISCUSSION AND FUTURE WORK

Our work is directed at enabling the development of personal robotic applications where robots do manipulation tasks for humans safely around humans. While many top software researchers are focusing on this research area, too often those researchers are not working on the best platforms. We see the availability of a capable, safe and robust platform for research in this area fundamentally changing the pace of progress in both research and applications. We see the ideal platform being a combination of great hardware and low-level software. To that end, we are working to build up the low level software along with the hardware presented here with the goal of making it available to software researchers in Personal Robotics as a platform that can be turned on and immediately used to generate new code and capabilities.

PR-1 represents a first step toward such a platform. We are currently proceeding with PR-2, a next-generation platform that will incorporate feedback from our experiences with PR-1 as a software development platform. We are working with industrial partners to make copies of PR-2 available to researchers from other institutions at the completion of its development. While we are early on our way toward our long-term goal, we look forward to an era when, in the personal robotics space, software developers can build on and leverage each other's results in a more effective way than is possible today.

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