Motivation and Design Considerations of a Compliant Mobile Base for Human-Centered Robots

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Abstract – Robotics is a growing field that has received tremendous support and focus in recent years. Backed by government and industry interests, robots now have the potential to move beyond traditional manufacturing setting into human-centered environments. Therefore, safety emerges as one of the most fundamental requirements in designing Human-Centered Robots (HCRs). To attain HCRs with high mobility and safe behaviors, we designed and built a torque-controlled omni-directional mobile base, Trikey 2012, at the Human-Centered Robotics Lab in Mechanical Engineering Department. Our design focused on reducing backlash, friction, uneven load distribution, and difficult assembly steps to create a high performance compliant mobile base for HCRs.

I. INTRODUCTION

Robotics could be one of the most transformative revolutions of the 21st century. In 2008, the National Intelligence Council published a report [1] that included Service Robotics as being one of the six most disruptive civil technologies by 2025. The other areas included technologies within the fields of bioengineering, energy, and cloud connectivity. The report further suggested that the most favorable scenario, "Autonomous World," is comprised of 1.) key advances in robotics R&D and 2.) strong support, funding, and regulation from government and industry. One of the end results would be "Robots [replacing] human workers in a number of skilled manufacturing roles, boosting the competitiveness of U.S.-based manufacturing." This introductory section examines the extent and significance of robotics today, with further focus in HCRs.

A. Trends for Robotics Today

In June 2012, President Obama's administration just announced the $50 million National Robotics Initiative (NRI), led by National Science Foundation to "grantees around the country for the development and use of robots that cooperatively work with people and enhance individual human capabilities, performance and safety [2], [3].” The NRI is founded on reasoning that robotics can addresses a broad range of national needs from domestic, commercial, to military. Notably in 2011, NASA has already sent off Robonaut 2 to aid the International Space Station, becoming the first dexterous humanoid robot in space [4]. In all significance, these are merely small parts of the national support for robotic research.

From the private sectors, multi-billion corporations have become increasingly involved in intelligence machines. Honda has long been developing the world renowned Asimo [5], a 4’3” bipedal humanoid robot, since the year 2000. Microsoft Kinect, a 3D scanning system initially aimed for home entrainment, has revolutionized 3D mapping for robotics as well. In March, 2012, Amazon spent $775 million on the acquisition of Kiva Systems, the creator of autonomous robots for shipping warehouses, to streamline shipping process [6]. Google, similarly, has several self-driving cars that have completed more than 300,000 miles of real world traffic as of August 2012 [7]. As a result, three U.S. states (Nevada, Florida, and California) have passed law to permit these autonomous cars on the road [8]. Along with multi-disciplinary corporations, application-focused robotic companies have also flourished. Intuitive Surgical, most known for its da Vinci surgical robot system, had USD $2.18 billion revenue in 2012 [9]. iRobot, responsible for a wide range of products from home vacuum robot Roomba to military-focused PackBot, had USD $435 million revenue in 2012 [10]. Furthermore, research-focused companies such as Boston Dynamics and Willow Garage are pioneers that are driving theses advances.

Besides consumer and U.S. administration support of robotic applications, we recently experienced the urgent need on an international level for robots to perform in disaster relief and humanitarian operations. On March 11, 2011, a magnitude 9.03 undersea earthquake impacted the shore of Japan and automatically shut down the nuclear reactors at Fukushima Nuclear Power Plant. Consequentially, the following tsunami flooded the emergency generators and crippled the cooling systems, which caused a catastrophic nuclear meltdown on par to the Chernobyl accident (both measured the maximum Level 7 on the International Nuclear Event Scale). To date, areas in Fukushima remain radioactive and unsafe for human operators. In December 2011, the Japanese government estimated that it would take the next 40 years to clean up and fully decommission the nuclear power plant [11]. From the initial aftermath, it was already apparent that reentering the partially damaged and heavily radioactive plant is crucial to retain control of the situation. However, it was also too dangerous for a timely and effectively human response. Eventually, teleoperated robots such as PackBot were used on-site and became essential tools for inspection; they provided important radiation recording in environments that would be lethal to humans [12]. These robots navigated though difficult terrains, such as debris-filled staircases, and highlighted the dire need for HCRs that can operate in human environments, along or in place of humans.

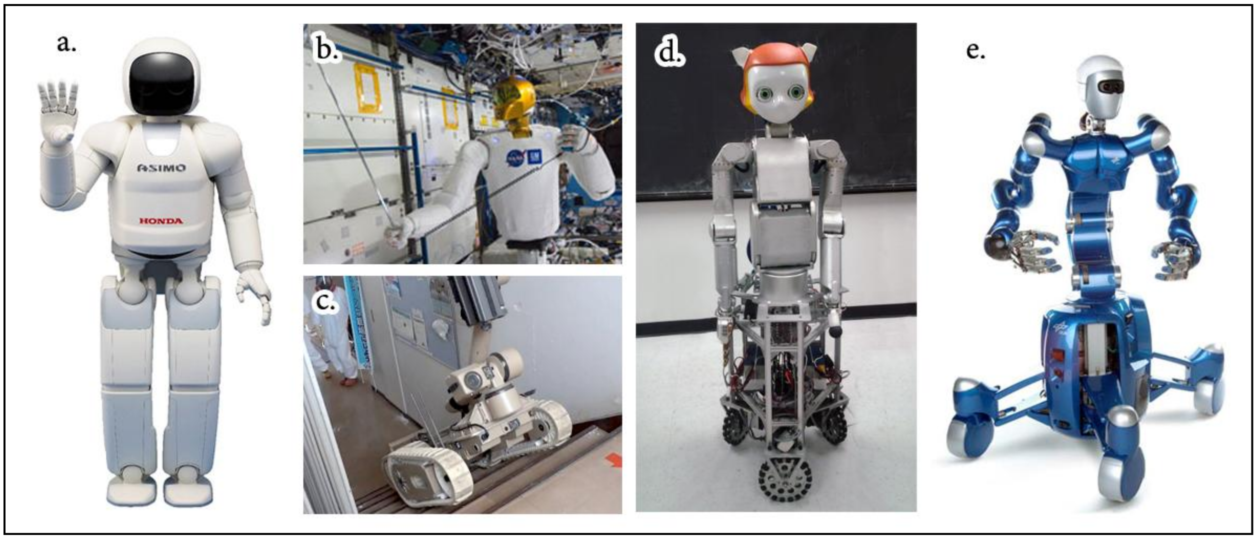

Figure 1. Various state-of-the-art robots: a.) Honda Asimo [5], b.) Robonaut 2 [4], c.) Packbot [12], d.) Dreamer [23], e.) Rollin' Justin [21].

B. Human-Centered Robots (HCRs)

Historically, robotic applications have been dominated by industrial needs, constituting a global market of USD $8.5 billion in 2012, mainly backed by automotive, electronics, and material manufacturing/handling [13]. However, today's position-controlled industrial arms are designed without compliance (defined technically as the inverse of stiffness, but also used interchangeably as the ability to sense, absorb, and react to force). This constrains them to operating only in factory environment and without the ability to engage in human interactions. However, as the technology advances, these robots now have the potential to spread beyond precision-based factories into human-centered settings such as homes, small businesses, and cities. Therefore, though HCRs can be either anthropomorphic or non-humanoid in design, they should all function with human safety as the most fundamental operating criteria. For example, there are multiple fields aiming to achieve safety, both preventively and reactively. Machine vision, motion planning, simulation, and sensor perception are all research areas that can identify and avoid dangerous situations preventively. In contrast, technologies such as low impendence actuators (motors with low stiffness) [14], soft flexible robots [15], or compliant control framework [16] can all damp and accommodate unexpected collisions.

Second to safety, HCRs must then have high mobility to navigate through common man-made terrains. A robot that could be easily obstructed by simple steps, gaps or curved surfaces is limited in its ability to perform mundane household or office tasks. While legged locomotion has advanced greatly, as evidence with BigDog [17] (an all terrain military quadruped) and other bipedal robots like Hubo [18] or Petman [19], wheeled platforms remain a proven alternative with high stability and energy efficiency. In conclusion, and regardless of means, effective and ideal HCRs should exhibit at least the following capabilities: safe interaction with human presence (planned or unplanned), mobility in rough terrain (urban setting), and precise manipulation in unconstrained environment (unlike industrial arms).

C. Goal of the Paper

Given the recap of support for robotics today, and the motivation for developing safe and efficient HCRs, the remainder of this paper presents the technical considerations used to design a compliant mobile base, followed by experimental results. With the goal to achieve safety in a reactive manner, Trikey 2012 is a wheeled mobile base with compliance as its primary design parameter. Furthermore, we focused on mechanical performance such as reducing backlash, friction, uneven load distribution, and difficult assembly steps to achieve compliant response. These considerations all have implications and applications to general engineering, especially force-sensing mechanical systems.

II. DESIGN

The Trikey project began as an introductory design project at a local high school in 2010. Under the guidance of our laboratory, the team built the first version with a wooden frame and a general outline for parts placement. Subsequently led by graduate students Somudro Gupta and Pius Wong, four iterations eventually integrated electronics (Meka Robotics LLC), torque sensors (Sensor Developments), motors (Maxon Motor), and all other essentials into Trikey-V.

Though operational, it suffered backlash and misalignments in the drive train, particularly from the inefficient miter gears and ill-designed frame assembly. Trikey 2012, as discuss in the scope of this paper, is a complete mechanical re-design during the summer of 2012. It consisted of designing in computer-aided design (CAD) software, sourcing components, machining, assembling, and testing. Therefore, the decisions and considerations we here forth discuss had the benefit of drawing on and comparing to previous designs and underperformance.

A. Mode of Transport

While an anthropomorphic design may seems desirable for its appearance alone in HCRs, dynamically stable legged locomotion is still an inefficient, dangerous, and developing area. As each leg requires at least three degrees of freedom (DoF)** to position its end effectors in space, bipedal or quadrupedal robots quickly increase in weight, cost, footprint, and especially control complexity. As an alternative to these complex DoFs, a system with three wheels would provide energy efficiency, great stability, and mechanical simplicity, allowing for more advance sensing and control. A detailed comparison of various state-of-the art wheeled platform can be found in [20]. For example, Rollin' Justin [21] employs four casters for mobility, which are wheels that can swivel on a pivot to change direction of rolling. In contrast, we settled on omni wheels in a triangular configuration to achieve a simpler omni-directional mode of transportation. Our selected omni wheels are 8 inches in diameter, with smaller unrestrained rollers around the circumference (Figure 2). These small ¾ inch diameter rollers can spin freely, giving a passive degree of movement perpendicular to the rolling direction. When coupled in a triangular configuration, three wheels create a holonomic driving system, meaning that three actuations match the three free DoFs (in x,y direction and θ rotation). This simplistic design minimizes constructing resources, and allows for more intuitive control algorithms (Figure 2). However, this design also amplifies one simple limitation: conventional wheels cannot roll over a disturbance higher than its radius. Hence, the small ¾ inch diameter rollers on omni wheels limit the base to traversing in mild indoor environments. In future upgrade of the systems, existing omni wheels design could be replaced by different configurations or sizes to increase mobility.

** For clarification, DoF is the parameter that defines a subject's configuration and location; for example, the human elbow has one DoF, the bending angle, to define its position.

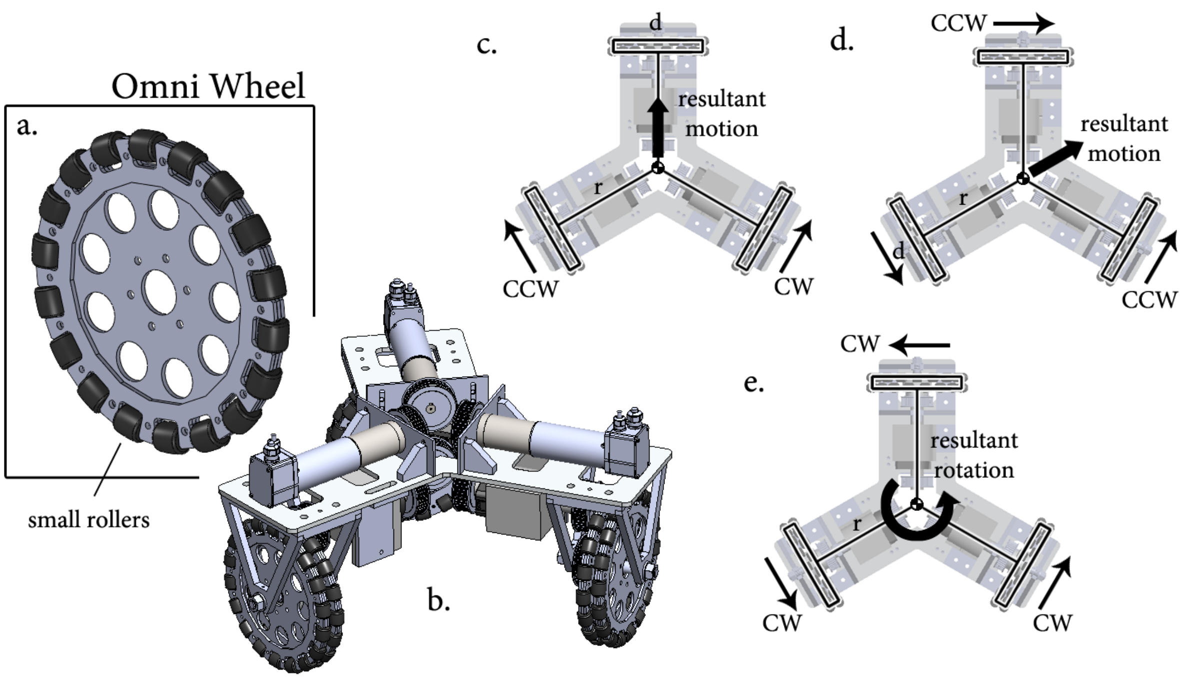

Figure 2. a.) isometric view of a single omni wheel, b.) model view of lower base assembly; for more information, please view Figure 3 for component details. c.) & d.) & e.) examples of operation from bottom view. CW represents clockwise wheel rotation, CCW represents counterclockwise wheel rotation.

B. Compliance and Backlash

As previously mentioned, safety is the most fundamental requirement for designing HCRs; In order for the mobile base to react safely during planned or unplanned collision, we focus on incorporating and improving torque sensing capability in Trikey 2012. With UT's Whole Body Controller (WBC), the control framework would ultimately translate these wheels torque reading to forces in the humanoid's reference frame, giving it the capability to counter disturbance [16]. With this in mind, there are several ways to achieve force and torque sensing. For example, emerging as a new promising research area, series elastic actuators incorporate a spring between the motor and output, hence force is calculated by measuring the spring deflection (Hook's Law: force = spring coefficient x deflection) [14]. In addition, there are other simpler and more robust alternatives using strain gauges, hydraulic, pneumatic changes. Off-the-shelf sensors usually come as a load cell package with all sensor circuitry included. Hence, we utilized a strain gauge based rotary shaft torque sensor for its precision, accuracy, and ease of implementation.

However, in order to take advantage of the torque sensor and maximize compliant performance, serious consideration had to be given to the drive train to minimize backlash. Backlash is the clearance between mating components, such as teeth in gears or pulleys. It is commonplace in almost all transmission, except in specialized gears like Harmonic Drive [22]. Backlash values in planetary gears usually range below one degree or one millimeter, negligibly small in traditional application. Unfortunately, in the case of torque sensing, backlash contributes to discrete spikes torque. The rotating load suddenly change as the teeth momentarily engages and disengages, creating undesirable impact forces. Control algorithms would then have difficulty in compensating these sharp changes of value to effectively achieve human-robot interaction. Furthermore, backlash is cumulative in a drive train; when the output is reversed in direction, the system would travel the total backlash distance before re-meshing with the input gear. In Trikey 2012, we reduced backlash by replacing the highly inefficient miter gear from previous design to low backlash timing belt. Even though backlash has been significantly reduced, residual back remains in the system due to planetary gearbox. To remove this backlash, future upgrade could use Harmonic Drive, which is a strain wave gear that utilizes the flexibility and elasticity of metal, deforming to the profile of the teeth mechanism.

C. Friction and Load Distribution

Besides backlash, friction also degrades the performance of the mobile base and torque sensing capability. Friction is the force that resists motion between solid or fluid surfaces, transferring part of the kinetic energy into heat, hence creating undesirable outcomes. First, an improperly designed robot with high friction would require more input force to safely steer and react to disturbances. Second, friction is difficult to model precisely. While frictional force is usually described as a linear function of normal forces (Force = Coefficient of Friction x Normal Force), it is merely an approximated empirical formula. The underlying physics are complex and nonlinear. Therefore, a control algorithm that finetunes a friction model would only be partially valid. Third, the static friction between the load and the sensing component dictates, hence limits, the responsiveness of the torque sensing. For example in Figure 2, the force from the environment would apply to the omni wheels, move through the bearings (friction source), transmit through the timing belts (friction sources), before finally deliver to the torque sensor. Therefore, if the bearings and timing belts have one newton-meter of static friction, external forces have to apply an equal amount before the mobile base starts moving or sensing the torque. The static friction model would then morph into a kinetic friction model. Furthermore, the same principle applies between the driving force and sensing component. To remedy this problem, consideration has been taken to decrease internal normal forces, and shorten the drive train path.

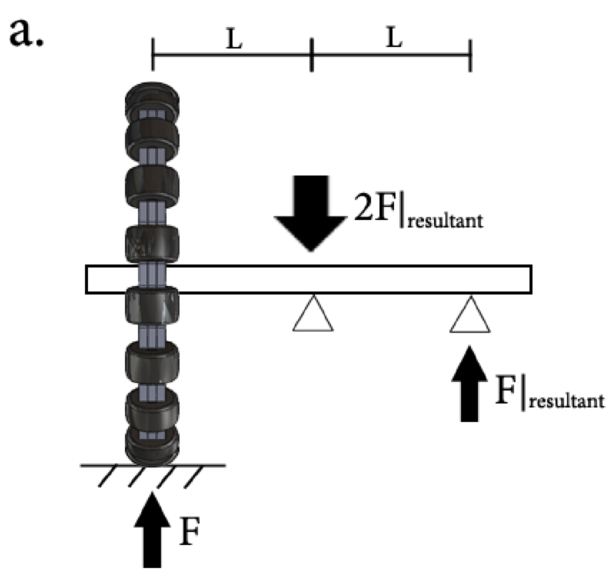

Figure 3. a.) wheel is mounted to the side like car tires, b.) wheel is mounted between supports like bike tires, a configuration that creates less internal reaction forces.

Figure 3 showcases the wheel-body configurations that negotiate between convenience and load distribution. On the left, wheel is mounted from the side like car tires, making the assembly more convenient, but it introduces a higher normal load on the support bearings due to moments. Notably, automobiles do not experience this moment imbalance since two wheels are connected to the same axle, a configuration impossible with our triangular wheels placement. Contrastingly in the diagram on the right, the wheel is slid up to the frame like bicycle tires. It requires the system to be lifted higher for assembly, but distributes the load more evenly, hence minimizing internal normal forces and friction. We employed the latter approach for Trikey 2012.

D. Assembly Consideration

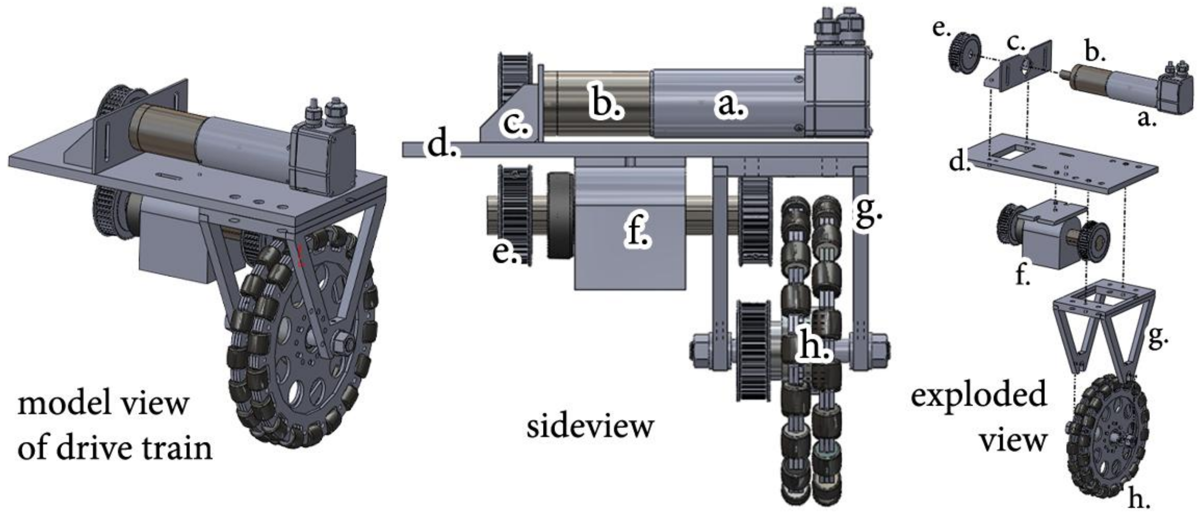

Figure 4. a.) maxon motor, b.) planetary gearhead, c.) motor mounting bracket, d.) base plate, e.) pulleys, f.) torque sensor, g.) wheels mounting frame, h.) double-stacked omni wheels

Before the complete mechanical redesign of Trikey 2012, the previous versions had a convoluted frame design. Structural elements were locked into each other; individual components were inaccessible without complete robot disassembly. In a research and development environment, it renders important maintenances, troubleshooting, and upgrades nearly impossible. This emphasizes that all good engineering design must keep ease of assembly and adjustability as a high priority. As shown in the Figure 4, each drive train component separately mounts onto the main frame, focusing on modularity. For example, a different motor can be adapted to the base plate by mounting bracket and pulley replacement. Common off-the-shelf parts, such as aluminum extrusions, are used frequently. They allow for versatile configuration of the electronics, computers, and battery systems in the overall mobile base design. In conclusion, it is also important to allowing for adjustments in every mounting element (for example, incorporate slots and bigger through holes versus using countersink hole).

III. RESULT

To validate the aforementioned considerations, an experimental comparison was performed after the construction of Trikey 2012 to highlight friction improvements. In the experiment, a step unit torque input of 0.1 N-m was applied to a free-floating wheel for one second on both Trikey 2012 and the previous base. The averaged angular velocity responses from a couple representative trails were recorded and examined in Figure 5.

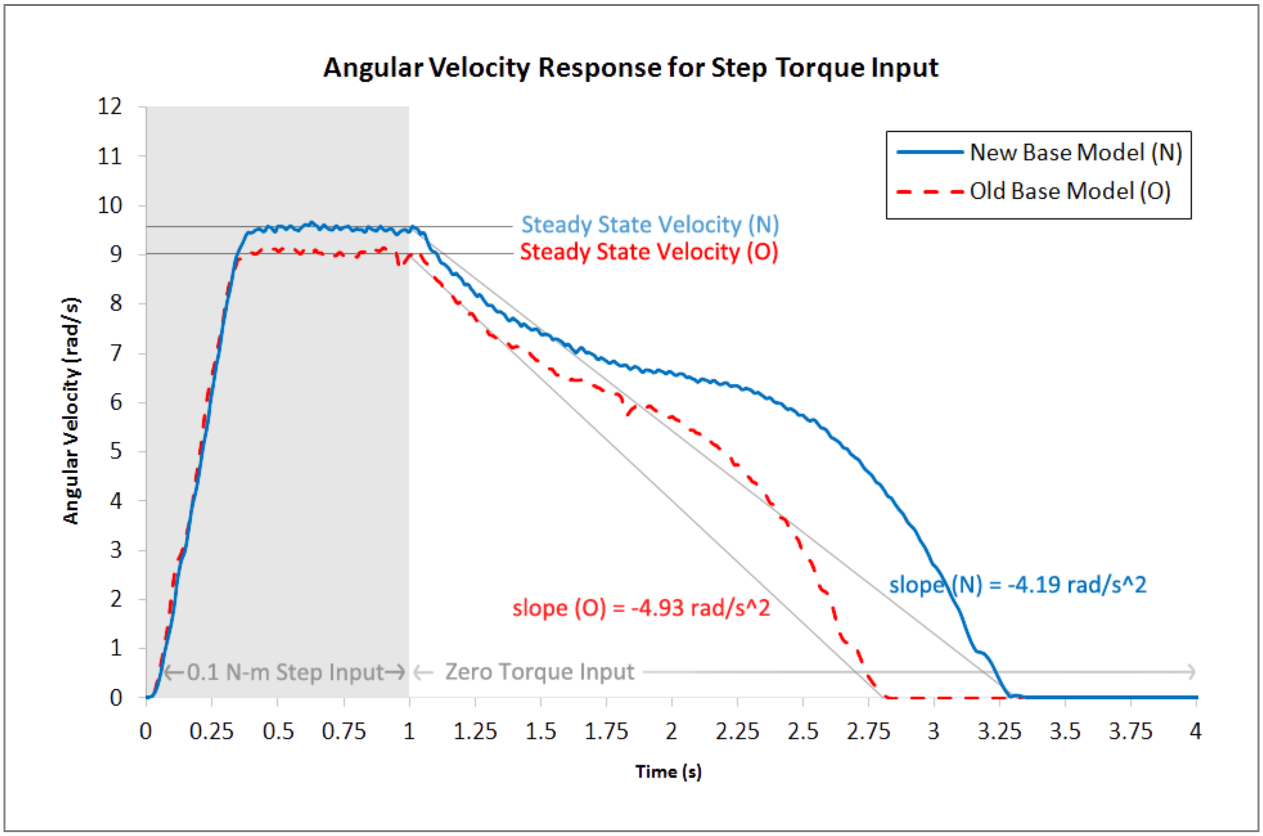

Figure 5. Experimental result of a unit step torque input for Trikey 2012 and previous model. Steady state velocities and deceleration rates are highlighted as criteria to examine friction improvements.

Without friction, a rotating system driven by a constant torque input would approach infinite velocity, with the slope dependent on inertia. Therefore, steady state velocity represents an equilibrium where the velocity-depended frictional force becomes equivalent to the input torque. From Figure 5, the experiment shows that Trikey 2012 (9.6 rad/s) achieves a 6.7% higher steady state velocity than the previous model (9.0 rad/s) for a 0.1 N-m torque input. And after one second of torque input, Trikey 2012 coasted to a stop at a 15% slower rate (-4.19 rad/s^2) than the previous model (-4.93 rad/s^2). While motor's back-EMF contributed to the coasting in both models, friction was the sole influence on the different performance. Therefore, Trikey 2012's drive train exhibited a measurable better performance (with lower friction) than previous model through this experiment.

IV. CONCLUSION

With the aforementioned considerations, we have designed and built a state-of-the-art mobile base with compliance ability. First, this paper gives a recap of the current state and support for robotics, such as U.S. administration's initiatives and industry's commercial pursues. Second, we introduce the need for Human-Centered Robots and propose several primary directives such as safety, mobility, and precision. Third, the paper discusses the significant topics we considered when designing Trikey 2012. In order to create safe HCRs, compliant is incorporated into the mechanical capability. Then reducing backlash, friction, and load distribution became design priority to achieve high-performance compliance. However, all these discussions were merely a small summary of the Trikey 2012 project. To limit the scope of the paper, and to cater a general educated audience, details about the electronics and control systems have been omitted. As they deserve discussion in their own light, please refer to [16], [20], [23] for further information.

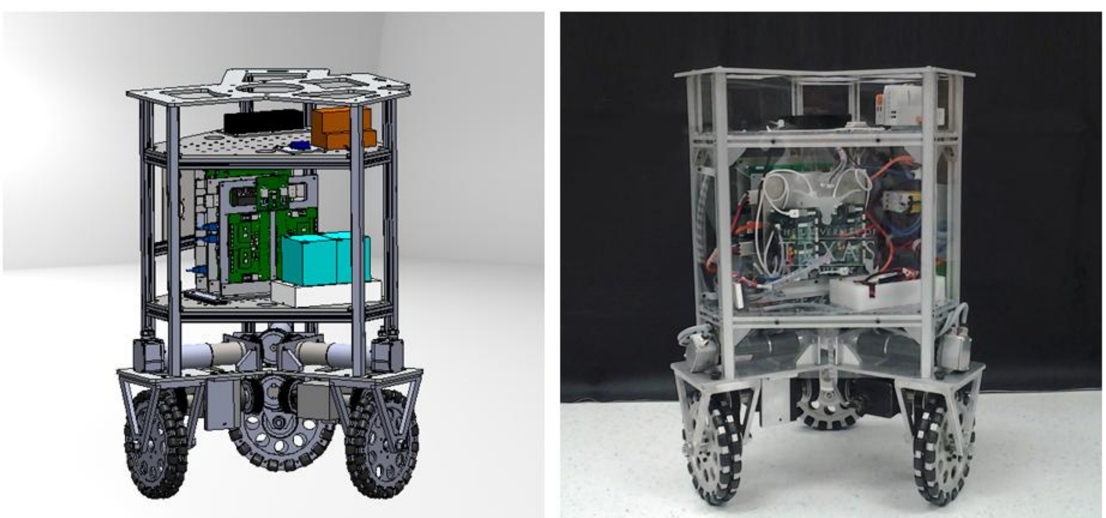

Figure 6. Left: Trikey 2012 in CAD software Solidworks, Right: picture of Trikey 2012

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