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Golem Krang: Dynamically Stable Humanoid Robot for Mobile Manipulation

Mike Stilman Jon Olson William Gloss

***Abstract*— What would humans be like if nature had invented the wheel? Golem Krang is a novel humanoid torso designed at Georgia Tech. The robot dynamically transforms from a .5 m static to a 1.5 m dynamic configuration. Our robot development has led to two advances in the design of platforms for mobility and manipulation: (1) A 2-DOF robot base that autonomously stands from horizontal rest; (2) A 4-DOF humanoid torso that adds a waist roll joint to replicate human torso folding and a yaw joint for spine rotation. The mobile torso also achieves autonomous standing in a constrained space while lifting a 40 kg payload. Golem validates our assertions by consistently achieving static-dynamic transformations. This paper describes the design of our mobile torso. It considers a number of factors including its suitability for human environments, mechanical simplicity and the ability to store potential and kinetic energy for handling heavy human and even super-human tasks.**

***Index Terms*— humanoid robot, dynamic stability, static stability, autonomous standing, robot design**

I. Introduction

What would humans be like if nature had invented the wheel? Golem Krang is a humanoid robot designed for service applications. Its anthropomorphic structure, with two arms and a two-DOF torso, is designed to store energy and utilize momentum in order to perform heavy tasks that match and exceed human capabilities. This platform was conceived and built at Georgia Tech in collaboration with Schunk GmbH. This paper describes the development of Golem which has resulted in two significant achievements: *(1) A 2-DOF mobile base that autonomously stands from horizontal rest; (2) A 4-DOF humanoid torso that adds a waist roll joint to replicate human torso folding and a yaw joint for spine rotation*. The robot torso also achieves autonomous standing in a constrained space, while lifting a 40 kg payload. We address the design challenges, solutions and experimental results that demonstrate the feasibility of a transforming humanoid robot.

Golem's ability to transform into a tall, dynamically stable state yields significant advantages for both navigation and manipulation. In [1], we show that dynamic stability allows the unprecedented capability to efficiently navigate *under* obstacles in constrained environments by storing and transferring kinetic energy. Furthermore, our work in [2] demonstrates that dynamic stability coupled with internal mass motion yields significant improvements for deceleration and adds to the safety of the robot in human environments. For manipulation, UBot [3] gives a static analysis indicating that dynamically stable mobile manipulators can move larger masses given the same actuation as their statically stable counterparts. In [4], we demonstrate and compare a range

The authors are with the Center for Robotics and Intelligent Machines & School of Interactive Computing at the Georgia Institute of Technology, Atlanta, GA 30332, USA. Emails: mstilman@cc.gatech.edu, jon@cc.gatech.edu, william.gloss@gmail.com

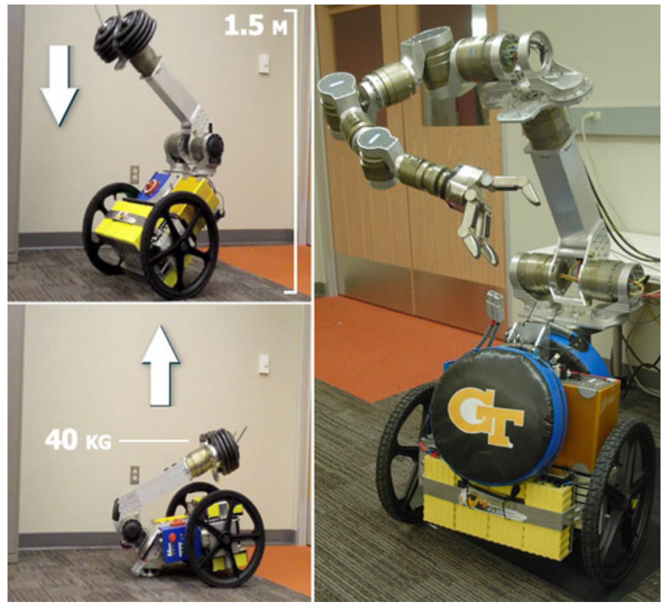


Fig. 1. Dynamically stable torso for energy efficient mobile manipulation. Golem Krang autonomously stands and sits with dynamic motion control.

of dynamic strategies that use dynamic stability to achieve increased performance for manipulation.

Some service tasks require static stability while others are better suited for dynamic stability. On the one hand, detailed manipulation that involves precise hand-eye coordination is best handled by a statically stable base which structurally rejects environment noise and forces. On the other, handling elevated or heavy objects is better managed by a dynamically stable base. Achieving robust static stability at 1.5 m would require a very wide base of support that is not suitable for human service environments. Golem is capable of both types of stability, making it well suited for all types of mobile manipulation and for the study of humanoids in service environments. We describe the considerations in design and implementation that led to this novel robot platform.

II. Related Work

Our research stands on two decades of achievements in robots for mobility and manipulation. Golem Krang is inspired by humanoid robots such as the Honda P1-Asimo [5, 6], U.Tokyo H6-H7 [7], Waseda Wabian [8] and the HRP series by Kawada and AIST [9, 10]. Another class of Golem's predecessors are wheeled mobile manipulators such as [3, 8, 11–14]. Such robots are compelling alternatives to bipedal humanoids due to the potential for increased stability and safety in human environments.

Typical mobile manipulators use a wide base of support yielding robust static stability [8, 11–13]. Others, such as the UBot [3], Robonaut [14] and BallBot [15] contact the ground with only two wheels or a ball. The latter systems are similar to bipedal humanoids since they use active control for dynamic balance, yielding greater physical capabilities and imrpoved efficiency as described in Section I. Golem Krang achieves both static and dynamic stability with its autonomous capacity to achieve any height ranging from a .5 m static to a 1.5 m tall dynamic configuration.

Existing manipulation platforms that autonomously stand use their arms and other kinematic articulation. [16–20] These robots require additional space for specialized links and actuators. They also perform slow quasi-statically motions to lift the torso. In contrast, our platform can stand quickly through dynamic motion without the need for additional space or specialized mechanisms. There exist numerous studies on dynamic lifting of multi-link inverted pendulums [21–23] as well as some practical experimental platforms such as iHop and Scwitchblade [24]. However, to our knowledge Terada's K1 [25] is the only mobile manipulator that can stand by generating sufficient angular momentum to dynamically swing the robot's center of mass over its feet. In contrast to all previous work, Golem Krang is the first to maintain a full three dimensional workspace for the robot arms, as shown in Figure 4, throughout the entire range of torso heights between .5 m static and 1.5 m dynamic configurations.

III. Design Considerations

The primary goals for our mobile manipulator were to maximize its ability to manipulate objects and maneuver through human environments. These considerations identified a set of design goals: First, the robot should increase its power by generating kinetic energy and storing potential energy by moving internal masses. Second, it should reach environment objects in any torso configuration. Finally, it should have a compact form factor that is suitable for human domains.

A. Dynamic and Static Stability

Humans stand upright and use their entire bodies to generate lever arms and moments when interacting with objects. [2, 4] They also brace themselves by sitting or leaning in order to achieve increased precision for delicate tasks. [26] Although we chose to use wheels instead of legs, we ensured that the capacity to perform both types of tasks was retained. Golem Krang was designed to autonomously transition from static to dynamic stability. In static mode, Golem's center of mass rests within a support polygon formed by a slider attached to the midsection and the two wheels. In dynamic mode, the robot stands on its two wheels, reaching a human height of approximately 1.5 m and allowing its entire body to support the execution of dynamic tasks.

B. Full Workspace

In either the static or dynamic mode, we ensured that Golem would be able to reach environment objects in order to perform manipulation. This consideration led to the design of the *waist joint* and formulated some of our design constraints. The waist joint allows the robot to fold its torso in half by placing the joint to one side of the wheel axle and the arms to the other. In principle, this allows the arms to

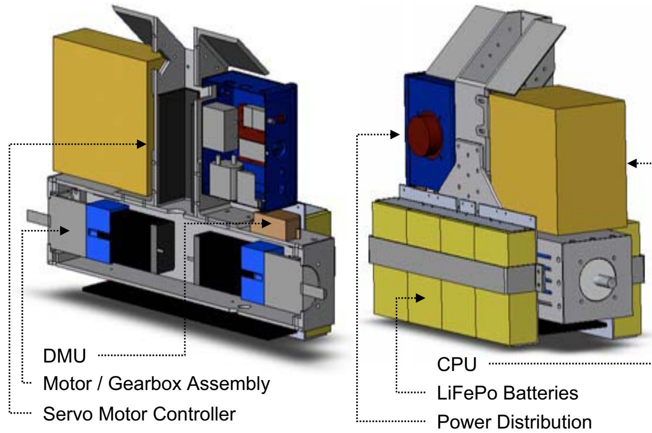


Fig. 2. Golem Base: Rear Section and Front Views

always be *ahead* of the robot. It also implies that significant mass must exist on the other side in order to bring the center of mass over the wheel axes at any stage of standing. This mass is accumulated due to the other robot components.

C. Accessibility

In order to ensure that Golem is able to work well within a human environment several design goal were based on the ADA requirements for public buildings. Frame and actuator sizing took into consideration ADA requirements such as minimum door and hall widths, minimum floor coefficients of friction and maximum ramp angles. This ensured that the robot has at least the same level of access as a human maneuvering a wheel chair. Since these are federal standards they guarantee that Golem Krang would work in any public space or building within the United States.

IV. Development of Golem Krang

Based on our design specifications, we evaluated a number of options for the mechanical, electrical and computational components of the robot. This section presents the final decisions and explains the rationale behind the choices.

Our primary goal for selecting components was flexibility. We aimed to make the platform as capable as possible. Consequently, aside from cost and weight, components were chosen to maximize power. ADA compliance provided guidance on the dimensions and the weight of the final robot.

A. Golem Base

The robot base was intended to function as a robot unto itself. We designed the base to be versatile enough to support any choice of torso design. Presently, it is a stand-alone inverted pendulum platform capable of supporting a large load of unknown configuration. Our final base design is capable of supporting at least 125 kg and autonomously transforming from static to dynamic stability. This section describes our selection of components based on physical structure, power, actuation, motion control, and computation.

1) Structure and Power: The base structure is an inverted-T formed from square aluminum tubing. This configuration is easy to assemble from simply-machined components and yields structural support that vastly exceeds our requirements. Furthermore, it offers housing for motors and gearboxes, and provides abundant external surfaces for mounting other components. The final base is illustrated in Figure 2. All electronic components in the system communicate over CAN. While all devices also receive power from a single source, the source itself can be selected and interrupted for individual components.

Robot power is supplied from either a high-current DC wall tether or a pack of onboard batteries. For long experiments the tether allows the robot to operate continuously. However, the primary mode of operation to date has been untethered using eight lithium iron phosphate (LiFePo4) cells connected in series. While other battery technologies potentially offer higher power-densities, LiFePo4 batteries safely source over 300 A of current, which is our estimate for whole body operation that involves heavy loads. Golem uses a management system that monitors the status of each cell and reports it to our on-board computer. Power is distributed from a single box with breakers to individual components. The box allows the user to select between wall and battery power and houses the robot's physical emergency-stop. Individual breakers provide correct current protection for each component and allow select components to be disabled during testing.

2) Actuation: Robot actuation required the ability to balance and drive the base itself plus a minimum of 60 kg representing the robot arms. This turned out to be the most difficult compromise in the design. We had to balance torque-output of the power-train against physical size. The inverted-T configuration described above dictated that whatever solution we arrived at had to fit within the confines of the base support. Additionally, our goal of making the robot ADA-compliant placed an upper-bound on the maximum width of the robot and thus on the length of each wheel's drive-train.

We selected brushless DC motors because they typically provide higher torque in a smaller, lighter package than their brushed counterparts. Based on dynamic simulations in Matlab, we derived the torque and speed requirements for the wheels. Given our choice of motors from Anaheim Automation (AA BLY343D), with peak torques of 4.2 Nm at 2000 RPM, we chose a 15:1 gear reduction to maximize system performance with regard to load bearing and recovery from imbalance. Since balance involves frequent changes in direction of motion with very small displacements, it was important to minimize gearbox backlash. For the base we selected planetary gears (AA GBPH-0902) as they provide efficient power-transfer, are backdrivable, and have a maximum backlash of 10 arcmin. For motor control, we selected servo controllers from Advanced Motion Controls (AMC DPCANTE-060B080) due to their support for CAN and ability to source 50 A to the motors in a small form factor.

3) Sensing and Computation: In addition to motor encoders, it was important to estimate absolute pose for robot balance. Linear accelerometers provide absolute pitch and roll for a robot at rest, but skew values under acceleration. Gyros provide absolute rotational velocities which, when integrated, give accurate rate estimates for pitch and roll over short time spans. To achieve accurate realtime pose estimation under moderate acceleration and realistic noise we chose to use a six axis inertial measurement unit (IMU). Golem is equipped with a Silicon Sensing 6-axis IMU (CIM00-15-0100PS) with a 1 kHz sampling rate and 16 bit precision. IMU data is passed through a Kalman filter, resulting in accurate estimates of pitch and angular velocity.

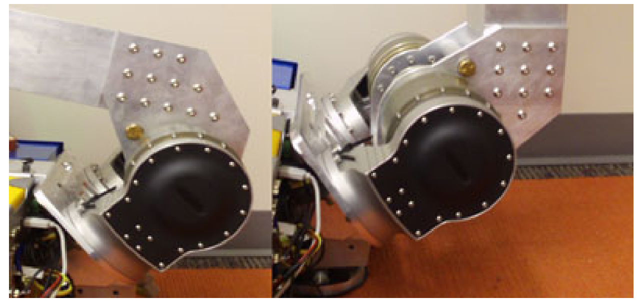


Fig. 3. Golem Krang waist joint: collapsed and partially expanded.

In terms of computational requirements we expected that the computer on the base would initially be responsible for control of the entire robot. We wanted to enable the broadest possible range of control and planning strategies, and at a minimum knew that the arms would introduce a substantial I/O requirement. All of these factors caused us to favor general-purpose industrial computers over small embedded solutions. We decided on the Aaeon AEC-6915 due to its abundance of on-board I/O ports, extensibility in the form of four PCI slots, ability to be powered directly from our unfiltered battery supply, and physical form which placed it precisely between structural supports.

B. Golem Torso

Golem's base connects with the Schunk LWA-3 arms through an extended torso. In static mode, the base is close to the ground and the torso folds onto it. Hence all the components on the base balance out the mass of the arms. The greatest challenge in designing Golem Krang's torso was choosing a physical structure that allows the torso to fully collapse and expand smoothly, quickly, and without interfering with the robot's workspace. Linear actuators, such as joints on large earth-moving equipment, lend themselves readily to the desired motion. However, actuators capable of providing sufficient lifting force for our 20 kg torso with its 40 kg payload were substantially larger and more cumbersome than the space on the robot. We selected rotary modules with BLDC motors and harmonic drive gears.

Our choice of rotary actuators required special attention to the design of a waist that would allow a fully collapsing torso. With simple inline designs the mounting hardware for the motors interfered with the closing action. Our design offset the mounts by $\pi/4$ rad on both the base and the torso. The resulting joint is shown in Figure 3.

The second consideration was the ability to rapidly expand this joint, allowing the robot to quickly *stand*. We calculated that Krang would need to lift a 40 kg load at the length of .75 m. It would require 294 Nm of torque $(40kg \cdot 9.8\frac{m}{s^2} \cdot 0.75m)$. A pair of Schunk PRL-120 modules identical to those used for the first and second link of the LWA-3 arm provide 372

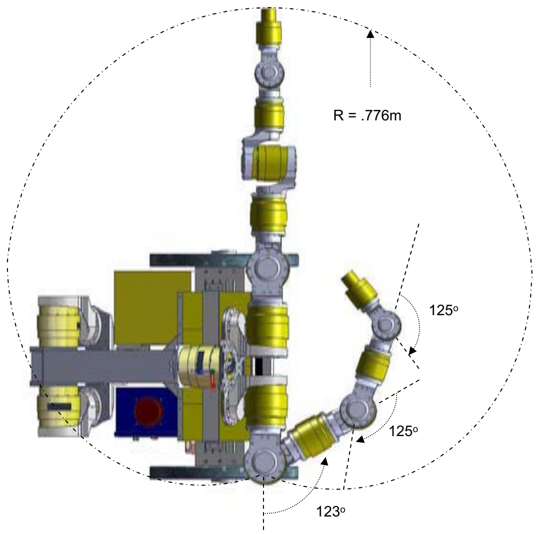


Fig. 4. The workspace of the robot arms during statically stable sitting. Image shows range of motion for one arm and joint limits for the other.

Nm peak torque as well as a magnetic brake that can be rapidly engaged and released. The brake allows Krang to partially expand or collapse the torso for extended periods without exerting constant lifting torque.

The angular offset and the use of the Schunk PRL-120 actuators yields a robot that stands to approximately 1.5 m at full height and is capable of collapsing to the point where the torso and base support columns are nearly parallel. Figure 4 illustrates the fully-assembled robot workspace during statically stable sitting. Notice that at any height between .5 and 1.5 m, the entire three-dimensional range of motion in front of the robot is accessible to the arms.

V. Control Design

The primary goals for Golem Krang's initial control system were simplicity and fault-tolerance. Currently, we are developing controllers that integrate balance and torso/arm motion to achieve complex dynamic behaviors. [2] However, the robot should not be reliant on them for operation. Therefore, we first segmented the control problem according to system components. Balancing is handled independently of torso joint and arm control. Likewise, locomotion is built atop the underlying balancing controller.

We first decided that all control on Golem Krang was to be carried out in terms of torque and therefore motor current. Torque is the direct physical analog of current. Our motors came sufficiently close to the linear model of an ideal DC-motor, $\tau = K_t \cdot current$. While current control is implemented on top of voltage regulation, voltage has no direct physical analog since torque at a given voltage also depends on motor speed and load. Current control allowed us to model the robot's dynamics as a pure mechanical system.

Further control decisions were informed by the sequence in which the robot was designed and built. We designed and assembled a functioning base months before the torso. Once the torso was ready to be mounted, we determined that the control scheme developed for the base was sufficiently robust to continue experiments. The overall structure for Krang's control system is a cascaded system as shown in Figure 5.

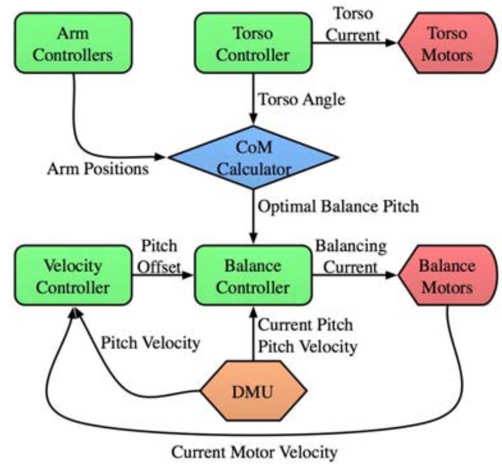


Fig. 5. Golem Krang control schematic.

Control for balance and locomotion of Golem Krang is handled by a cascade of proportional integral differential (PID) controllers with minimal modeling of the actual system dynamics. Balance depends primarily on the robot's center of mass (CM). The balance controller is provided with a target balance angle that places the CM directly above the wheel center by summing the gathered mass contributions from each of the robot links. This information is provided by the other active controllers. The balancer is a PID controller over motor current that drives the system to a desired angle.

Robot velocity is controlled by providing the balancer with an offset from the optimal pitch angle. As the balancer strives to maintain this angle, the robot accelerates in the direction of the tilt. For any given acceleration there exists a tilt-angle at which gravitational forces are perfectly balanced against the lifting force generated by maintaining the robot's acceleration. A small integral term enables the robot to discover and hold the appropriate angle for any given velocity assuming some energy losses due to friction. The same controller achieved a zero velocity on a slight slope.

Control of the torso is handled via current control of the waist joint actuators. The balancer computes the CM from joint positions. If the robot carries an unknown payload, the calculated CM may be incorrect and the robot may start to drift. However, the velocity controller integral term corrects the motion by adjusting the target offset.

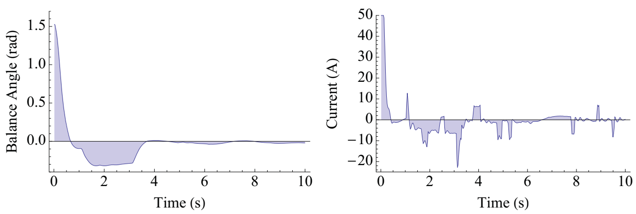
The static-dynamic transition is managed directly by starting or stopping the PID balancer loop. For standing, the balancer is given the CM based on data from other controllers. It immediately observes a substantial error in angle. To correct for this error it applies a large current to the motors and causes the robot to spring rapidly from its static position to its dynamically stable equilibrium.

VI. Experimental Results

Golem Krang was constructed in stages. We developed the robot base, added the torso, and later weights for the arms. We observed that the mobile base was capable of autonomous standing from horizontal rest. This behavior was extended to lifting the torso and supporting the full weight of the final robot. This section gives the experimental results achieved during each stage of robot development.

(a) 0s (b) 0.3s (c) 0.9s (d) 2.0s

Fig. 6. Golem Krang Base autonomously standing from horizontal rest.



(a) Standing angle (b) Standing current

Fig. 7. Golem Krang Base autonomous standing current and tilt angle.

A. Golem Base

For the base alone, we achieved our goal of producing a fully functional mobile robot. As shown in Fig. 6 and 7, the base is capable of rising from horizontal rest, just over 1.5 rad to its dynamically stable equilibrium.

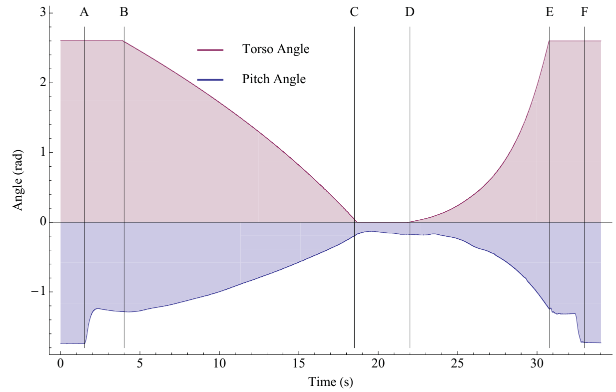
In our experiments, the dynamically balanced base supported a payload of at least 125 kg. It achieved a peak acceleration of 5.6 m/s^2. We have verified its ability to be driven through ADA compliant spaces including single-width doorways and over various terrain such as carpet, tile, brick, concrete, gravel, grass and ramps.

B. Complete Golem Krang

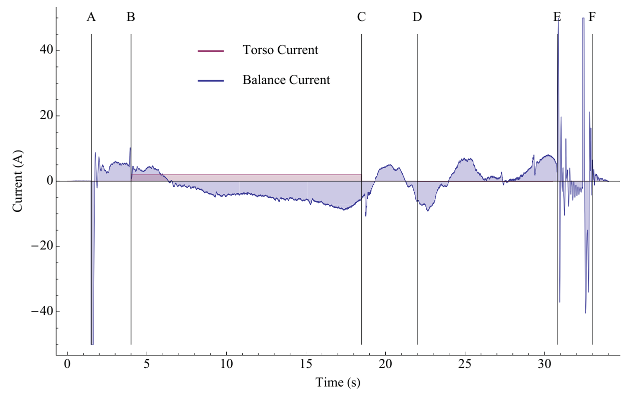
The addition of the torso required some changes to Krang's balancing model. As the waist-joint opens and closes the robot's center of mass changes. The balancer was modified to incorporate the optimal pitch as a parameter that could be updated in realtime based on the positions of the torso joints. Consequently, the robot was able to transition from static rest to dynamic balance and perform expansion and collapse of its torso while maintaining balance.

Figure 9 shows complete cycle of the robot's configurations and the currents required to achieve them. At time zero the robot is sitting in a statically stable configuration with the base fully collapsed. At point **A** we trigger the transition from static to dynamic stability. Once the robot has achieved dynamic stability we begin opening the torso at point **B**. To open the torso we apply a fixed 2.5 A to each of the PRL-120 modules. By point **C** the torso has fully opened and the robot is standing at 1.5 m in height. At point **D** we begin collapsing the torso by applying a small -0.1 A current allowing gravity to supply most of the closing force. The robot is fully closed by point **E** after which we ask it to transition back to static stability which it has completed at point **F**.

The robot maintains its balancing and locomotive capability through the entire range of motion. The slider used to provide static stability allows the robot to be driven over smooth surfaces in this mode. Figure 10 shows Golem's transition from static to dynamic stability and back. For these trials the torso position was kept static using the magnetic break, so that the robot can be treated as having a fixed optimal balance pitch. The x-axis of graphs a and c has been positioned at this optimal balance angle to more clearly illustrate the robot's convergence to dynamic stability.



(a) Full stand/sit torso and pitch angle



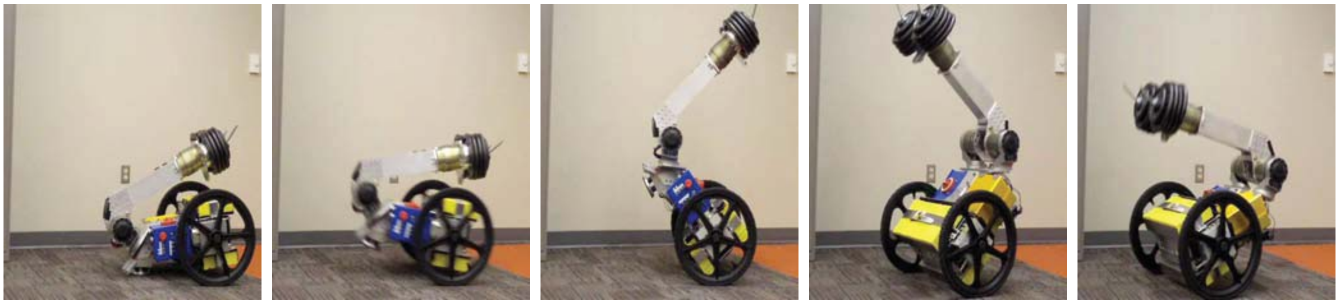
(b) Full stand/sit torso and balance current

Fig. 9. Golem Krang Torso transitions between static and dynamic stability as well as standing to full height.

VII. Discussion

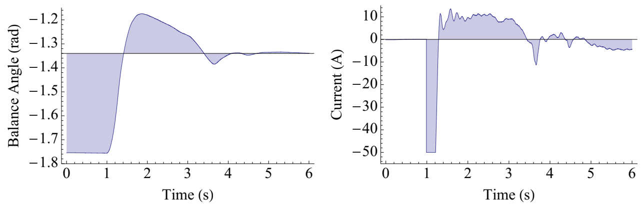
Golem Krang is a new humanoid robot capable of full access to its workspace in both static and dynamic stability modes. Golem is able to maneuver and transform between the two modes in a restricted environment through dynamic motion. This allows the robot to perform a wide variety of tasks involving both gross and fine motor skills.

The short term goals for Golem Krang are the addition of a sensor suite and manipulation planners. The robot will recognize its environment and manipulate it to achieve mission-level goals. In the long term, it will perform a wide range of humanoid tasks ranging from hospice care to small and medium factory automation.

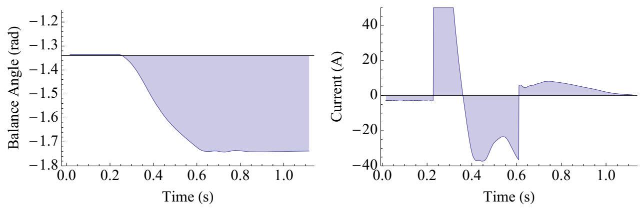


(a) 0s (b) 1s (c) 9s (d) 21s (e) 30s

Fig. 8. Golem Krang Torso autonomously standing and sitting: movement from static to dynamic balance and back.



(a) Standing angle (b) Standing current



(c) Sitting angle (d) Sitting current

Fig. 10. Plots of Golem Krang Torso autonomously standing and sitting.

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