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The HERMES Humanoid System: A Platform for Full-body Teleoperation with Balance Feedback

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***Abstract*— The HERMES humanoid robot system is designed for studying whole-body human-in-the-loop control with balance feedback. Inspired by the innate physical control capabilities of humans as well as the capacity for creative learning, we explore the use of the full-body of the human operator as the controller for a humanoid robot. The state of balance of the robot is displayed as sensory feedback to the human operator applied as force to the waist in order to stimulate corrective teleoperated control actions. This paper addresses the design considerations for such a system and shows initial results for human-in-the-loop-balance control as well as a wall-breaking demonstration that summarizes the breadth of capabilities of the system. Initial results show that the operator can respond to an impact disturbance on the robot within 175 ms and 125 ms after the robot's center of pressure begins to move.**

I. Introduction

Disaster response has long been considered the ideal application for robotics but current robots have failed to address the needs of the recent incident at the Fukushima nuclear power plant [1]. Track-robots have entered and partially traversed the rubble in order to survey the area, a formidable challenge in itself. However, there have not been any robots that possess the ability to navigate the highly unstructured environment as well as do physical work inside of the facility such as lifting, pushing or breaking through impact, a combination of tasks that a typical human would be able to do.

We identify two major needs for robots that humans can achieve with ease: the ability to 'creatively' handle highly unstructured environments, and the ability to stably manipulate objects with high force using its own dynamics to maximize the capability per volume - a bigger and heavier robot will be stronger but might not be able to go through the space designed for a human. Current artificial intelligence is far from 'creatively' tackling situations even in a very simple situation, particularly when dynamic movements or dynamic interaction with environments are required[2]. We believe that direct human-in-the-loop approach with appropriate sensory feedback will enable virtual presence of an operator and dramatically improve the performance of robots in disaster situations. If the robot is sufficiently anthropomorphic and the operator receives the proper sensory feedback, the operator can leverage the innate control ability of its own body to control the robot including the balancing. In this paper, we introduce the teleoperated HERMES humanoid robot system with the Balance Feedback Interface shown in Figure 1 that addresses these key deficiencies.

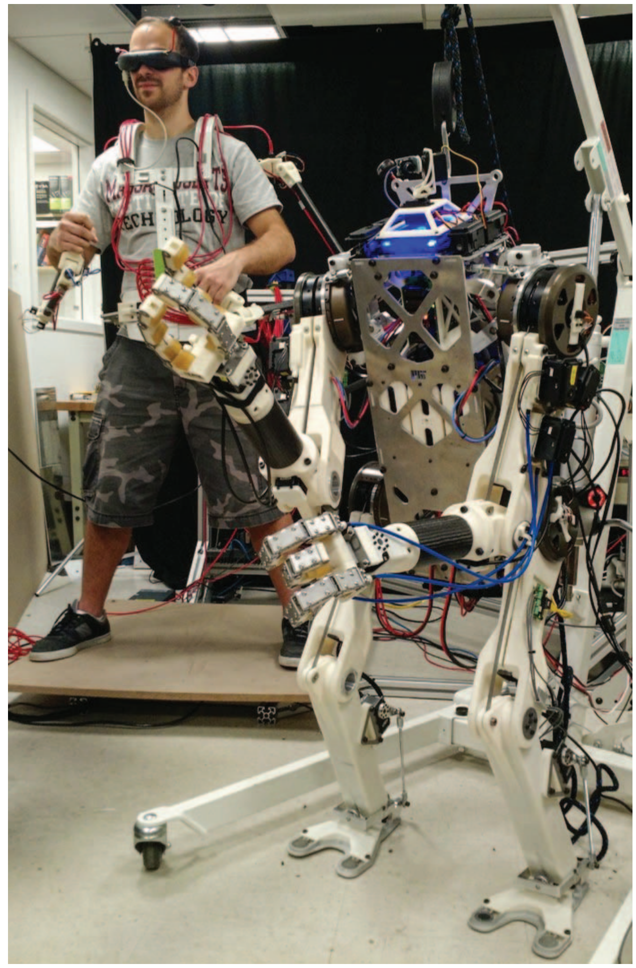

Fig. 1. The HERMES humanoid system showing the operator and humanoid robot. The operator is standing inside the balance feedback mechanism and is wearing the upper body motion capture suit.

For humanoid robots, maintaining balance is crucial to accomplishing any manipulation task and one that has not been well addressed by whole-body teleoperation. Furthermore, complex momentum control of the human body is essential for many tasks such as swinging a hammer, and opening a heavy spring-loaded door. Previous model-based posture control approaches successfully stabilize the body but are unable to interpret and execute the operator's intention of complex movements in various situations [2],[3]. Nor are they used to provide feedback back to the operator [4],[5],[6].

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[2]Manufacturing robots are optimized for position control and are usually not capable of force control tasks such as dish washing, cleaning a car without damaging it

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In addition, these approaches are highly dependent on prior knowledge which is prohibitive for high force manipulation in unknown disaster environments.

Visual feedback, commonly used in teleoperation gives no indication of changing balance conditions until movement occurs. Often when tipping is observed on camera after a significant vision processing delay, there is little that can be done. Humans however, are able to achieve balance naturally through a multitude of sensors in the body (vestibular, proprioceptive and visual) [7]. Furthermore, humans can creatively use strategies that proactively suspend balance control when it conflicts with a task, such as dynamically shifting body mass to open a heavy spring loaded door.

In this study we explore the use of the operator's entire body as the control input to the humanoid robot and develop a force feedback to display the robot's balance state in an intuitive way. Previous efforts using joysticks [8] or indirect mapping of operator hand movements to robot body movements [9] cannot use intuitive reflex responses without significant prior training. Upper body teleoperation systems such as the RE^2 HDMS [10] and DLR JUSTIN [11] provide a haptic immersive experience for manipulation and we extend those principles to full body balance.

By immersing the human operator in the experience of a humanoid robot body during teleoperation, the operator can rely on the intuitiveness of its own control frameworks for coordination. Existing work has addressed visual feedback from the robot, but an open area of research is how to display nonvisual, non-audio balance information back to the user. For instance, with properly identified and tuned feedback, the robot falling could transmit the feeling of falling to the operator and any reflex-based corrective action could be mapped back to the robot to correct its balance.

In addition to the intuitiveness of whole body human-in-the-loop teleoperation, there are distinct advantages in capturing human movement. First, the learning capability of the human will be able to compensate for the differences in dynamics and kinematics between the robot and operator. This is a property shared across all teleoperated systems. Second, the system can observe strategies of the human for balance in response to a stimulus and use these data to synthesize autonomous strategies for the robot. We expect that over time, not only will the operator learn to use the robot, but the robot will be able to correct for aberrations in the human control as well as exceed human performance, given that robot can adequately anticipate the command. Third, the human interface side can observe the correspondence between applied force to the human and the human's response to better formulate feedback strategies to the operator. Finally, as long as the robot is sufficiently similar to the human operator, this strategy can reduce the reliance on purely model-based approaches. Unexpected perturbations as well as loading conditions due to handling heavy objects will be felt similarly as disturbances to the balance of the robot.

This paper is the first to explore the system design for full body human-in-the-loop balance control with balance feedback. Section II addresses the system design principles. Section III show the major design components of the humanoid robot and section IV presents results from preliminary strategies for balancing with the human in the loop.

II. Principles of full-body teleoperation

A. Anthropomorphic design of the humanoid robot

While teleoperation using joysticks has been readily explored, to provide an immersive experience for the operator, the humanoid robot should move similarly to the human operator. Therefore, HERMES is designed with dimensions scaled to approximately 90% human of an average human female. At that size, the robot is able to interact with human designed environments and operate tools. The arms however are longer to match the leg length so that the robot will be capable of quadruped locomotion in the future.

B. Balance feedback and motion capture of the operator

In order to create the immersive telepresence experience, the operator stands in a Balance Feedback Interface and wears a motion capture suit that is used to command the robot posture. Design details are provided in [12] as well as in a companion paper [13]. The center of pressure (CoP) is used as the measure of balance for the robot and it will stay within the boundaries of the support polygon formed by the convex hull of the feet when the robot is dynamically stable [14]. The Balance Feedback Interface applies planar forces to the operator's hips that correspond to the movement of the robot's CoP in order to maintain the CoP inside of the support polygon. The mapping between the CoP position inside the robot's support and the force vector on the operator is constructed with a potential function described by equations 1 and 2.

$$V = f(\overrightarrow{x_{CoP}}, SupportPolygon) \tag{1}$$

$$\overrightarrow{F_{operator}} = -\frac{dV}{d\overrightarrow{x_{CoP}}} \tag{2}$$

For the strategy explored in this paper, when the CoP of the robot approaches the boundary of the support polygon, an increasing force is applied to the operator in the direction of movement away from the boundary. We expect the human operator to comply to the force and move in the direction that regains balance of the robot. That is, if the robot is tipping too far forward, the Balance Feedback Interface will apply a backward force on the operator's hips. The resulting hip motion is mapped to the robot so that a backward movement of the operator will move rotate the robot's torso backward. Since the motion of the operator's upper body is also mapped to the robot, the operator can choose to use other movements to correct the balance. This is the first exploratory test using a simple feedback strategy and future strategies will incorporate more knowledge of human reflex actions and robot dynamics. An example of future study includes using Capture Point and stepping to maintain balance [3].

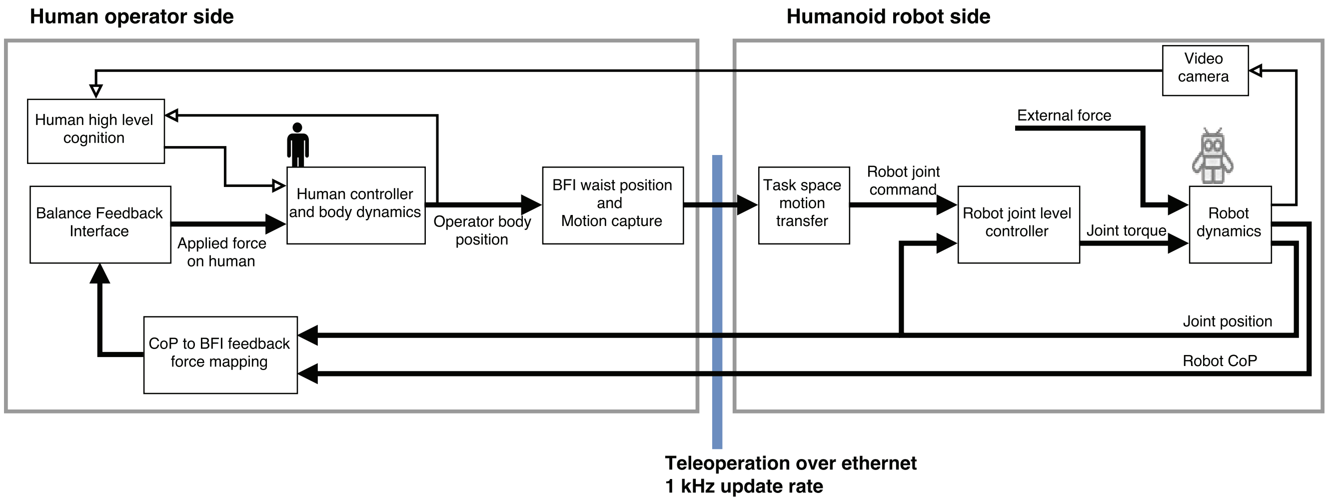


Fig. 3. Block diagram of HERMES system with human-in-the-loop feedback. The bold arrows show the balance feedback loop in which the operator uses non-visual force feedback on the waist in order to stabilize the robot. The open arrows show the feedback path of visual data and higher level cognitive planning.

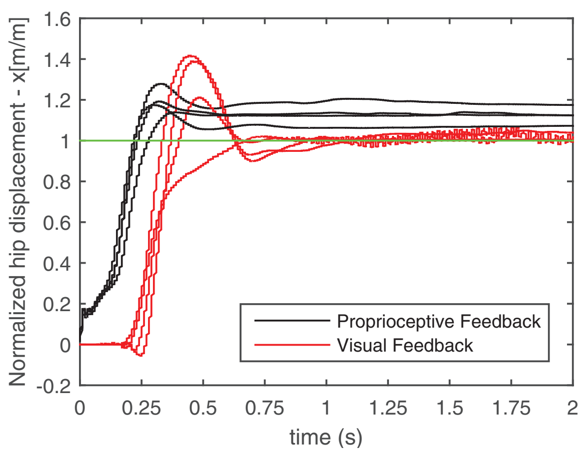


Fig. 2. Human hip displacement due to step input of proprioceptive stimulus force on hips and visual stimulus

C. System design

Seamless virtual telepresence for the operator requires management of dynamics and delays of the entire feedback loop with the humanoid robot. Human proprioceptive reflexes have response times of 50 - 100 ms [15] and visual processing response times on the order of 200-250 ms [16] depending on the subject. We predict that for the strategy of balance feedback information displayed as force on the operator's hips, the reaction time after training should be between that of proprioceptive reflexes and visual processing.

To justify the hip force feedback strategy rather than visual, a hip position step reference is presented as proprioceptive input at the hips and through visual input. Four trials of each type of sensory feedback are presented in Figure 2. These show that proprioceptive response time is $\sim$100 ms faster than the visual response. Therefore, force feedback on the hips should allow for more dynamic teleoperation performance compared to visual feedback.

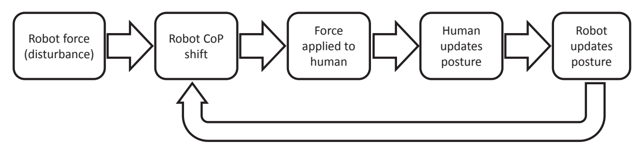


Fig. 4. Flow diagram showing the expected sequence of events for human in the loop balance feedback

A block diagram showing the overall control architecture of the system is shown in Figure 3 and expected sequence of events is shown in Figure 4. The characteristic time constants of major components in the system are listed in the Table I. System components related to computation and data transmission are set to 1 ms to minimize additional delay on top of physical dynamics.

In typical operation, the system works as follows. Operator posture is captured by the Balance Feedback Interface and motion capture suit. These are transmitted over ethernet to the robot which transfers operator task space motions to robot coordinates. The robot controller carries out the commanded motion and the load cells in the feet monitor the center of pressure. The center of pressure data is transmitted over ethernet back to the Balance Feedback Interface which then determines the proper feedback force command on the operator. Force is applied to the operator's waist and the resulting motion of the operator is captured and commanded to the robot.

III. Design principles of the HERMES humanoid robot

The HERMES humanoid robot is 45 kg and sized to approximately 90% of an average human female. The hip height is 730 mm and the shoulder axis height is 1105 mm. Each limb has 6 degrees of freedom: 3 at the shoulder/hip,

TABLE I

TABLE OF TIME CONSTANTS FOR COMPONENTS IN SYSTEM.

System component	Characteristic time constant
Human controller and body dynamics	
Human proprioceptive reflex action [15]	$\sim$ 50 - 100 ms
Human visual processing [16]	$\sim$ 200 - 250 ms
Anticipatory postural adjustments [17]	$<$ 0 ms
Experiment	
Human hip proprioceptive response	100 ms
Human hip response to visual stimulus	200 - 250 ms
System computational delay	
Motion capture of human	1 ms
Ethernet communication delays (2x)	2x 1 ms
Task space motion transfer	1 ms
CoP to BFI feedback force mapping	1 ms
Video camera (30 frames/sec)	33 ms

1 at the elbow/knee, and 2 at the wrist/ankle. The following are major design features that consider the maximization of force control bandwidth and overall system bandwidth while providing features that allow the robot to accomplish human-like manipulation tasks.

A. Major motor axes operate on power planes

The HERMES robot is designed to do most of the high force work on 'power planes'. We define these as the planes in which the movement of the end effector occurs due to the parallel axis shoulder and elbow motors (in the lower body, the hip and knee). To maximize energy efficiency, high force movements such as hammering or throwing generally involve swinging a mass on a single plane. In order to maximize capability without adding significant weight, major work is expected to be done on these planes. If the humanoid is unable to reach a position with these planes, the operator can reorient the robot and replan the movement. Like humans, these planes are typically close in alignment with the sagittal plane of the robot and can deviate slightly. Since highly dynamic motions are executed in the power planes, the majority of the actuator mass in the robot is allocated to the power plane motors. The actuators used on the power planes are custom large gap-radius motors that are shared with the MIT Cheetah robot [18]. The remaining yaw and roll axes of the shoulder/hip are driven by a parallel actuator mechanism by two Dynamixel MX-106 compact servo actuators with custom electronics. These lower power, lightweight actuators are used to reorient to 'power planes'. Figure 5 illustrates the power plane concept.

B. Limb design

In order to minimize inertia of limbs for high bandwidth, the manufacturing was focused on high stiffness composites. The main structure is provided by commercially available braided carbon fiber tube. Complex interface geometry for mounting the limbs to the motors and the mechanical attachments made from ABS on a Stratasys uPrint 3D printer. The hollow ABS parts are then glued over the carbon fiber tube. A cross sectional view is shown in figure 6. To aid the design of parts in FEA, several experiments were conducted

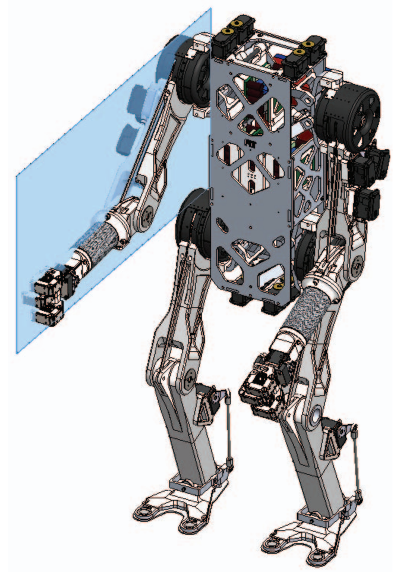


Fig. 5. CAD drawing of the HERMES humanoid highlighting the power plane on the upper right limb

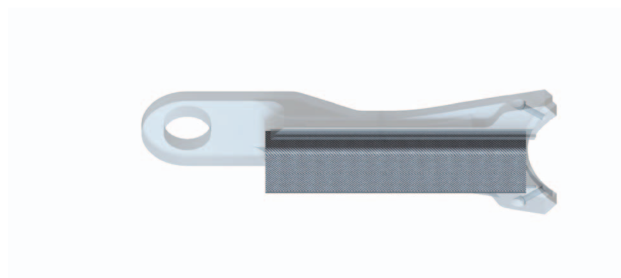


Fig. 6. Cutout view of the HERMES robot composite leg design.

on solid cast ABS and the 3D printed equivalents. 3D printed parts were found to have 90% of the weight and 85% of the stiffness compared to solid ABS. Final limbs on the HERMES robot have higher stiffness/weight ratio compared to a similar aluminum part.

C. Foot design

The design of the foot is shown in figure 7. Each foot contains 3 contact points, each instrumented with a load cell that together provide an estimate of the center of pressure of the robot inside of the convex hull corresponding to the support polygon. Three load cells provide a minimal estimate of the CoP even when only a single foot is in contact with the ground.

D. Hand design

For a disaster situation, hands that can grasp basic shapes such as an axe or door handle, yet have the strength to move or demolish rubble are necessary. Additionally, the hands must follow the overall design philosophy of the robot in making the limbs as light as possible to reduce inertia during dynamic operations. This was accomplished by utilizing three cable-driven underactuated fingers which

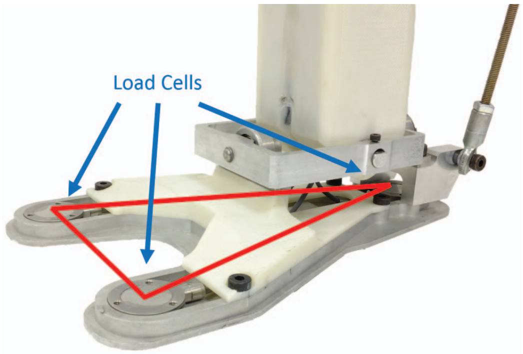


Fig. 7. HERMES humanoid robot foot showing the location of the 3 load cells.

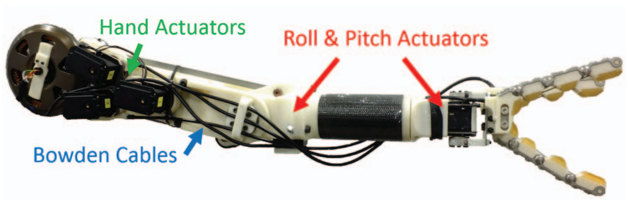


Fig. 8. Arm of the HERMES humanoid robot showing the location of proximal motors driving Bowden cable that actuate the fingers.

allows the actuators to be mounted proximal to the body as seen in Figure 8.

To accomplish grabbing task, the fingers close until the object is fully bounded due to underactuation as Figure 9 demonstrates [19]. To support the robot when moving or be used as a tool themselves, the hand can also make a rigid fist.

The lower arm allows for 360 degrees of roll through an integrated motor towards the elbow, while the wrist provides 180 degrees of yaw movement.

IV. Experiment

A. Single Impact disturbance recovery

In order to characterize the performance of the balance feedback system, the time trajectory of motions and forces in the system were monitored while applying a disturbance force to the robot. An instrumented mallet with a load cell

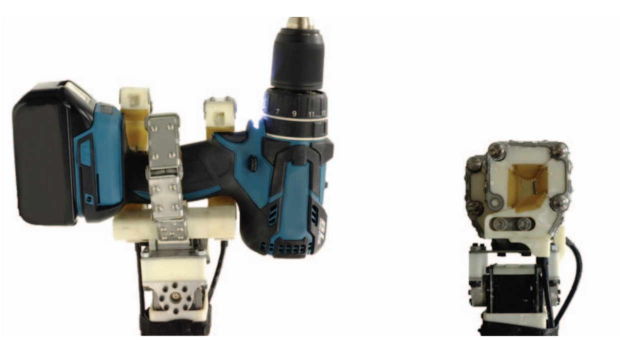


Fig. 9. Hand of the HERMES humanoid robot showing a grasp of a power drill and a fist. Note that the fingers can independently actuate the drill power switch.

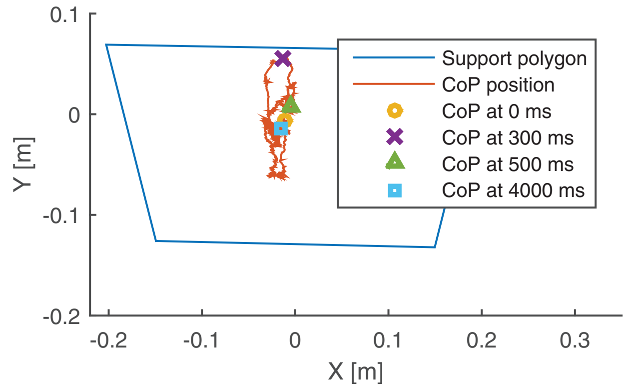


Fig. 10. The trajectory of the robot CoP inside of the support polygon from 0 to 4 seconds after the impact disturbance.

was used to apply an impact disturbance at the top back edge of the body frame in the forward direction. The change in robot balance due to the disturbance is measured by the load cells in the feet by computing the change in center of pressure. When the robot CoP approaches the edge of the support polygon of the feet, a force is applied to the operator in the direction that the CoP should move to keep the robot balanced according to a potential function described in Section II-B. The operator then commands corrective motions which are mapped to the robot posture. In these experiments, the operator uses a hip strategy to control the robot. Forward planar displacement of the operator's hips commanded forward tilt of the robot torso at the robot hips with a gain of 5 rad/m. This gain was chosen empirically so that the operator possessed sufficient control authority to command large robot torso tilt angles that could cause the robot to lose balance, all while being able to maintain its own balance. Vertical displacement of the operator hips was mapped to the robot hip height.

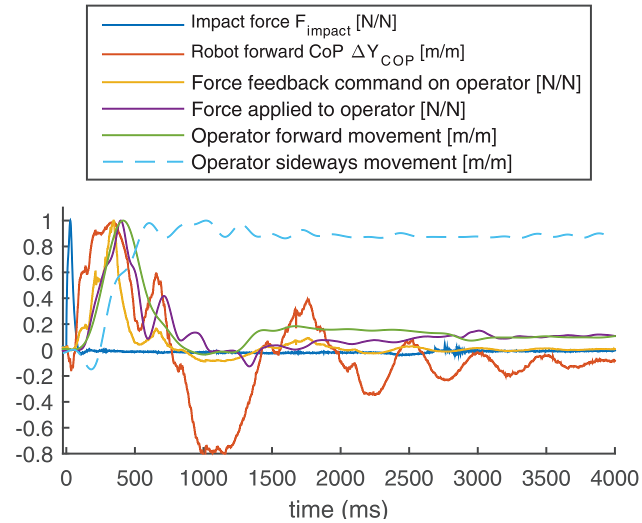
Experiments were conducted with two different operator knowledge conditions. In the first experiment, the operator had no knowledge of when the impact was going to occur and had to rely on the feedback from the Balance Feedback Interface for the robot state of balance. In the second experiment, the hammer impact on the robot was preceded by an audible countdown so that the operator could anticipate the change in robot CoP.

B. Impact Disturbance Recovery Results

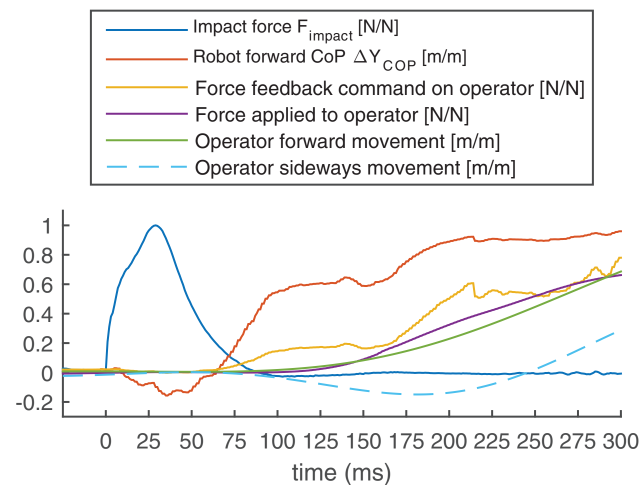
Results of impact disturbance experiments in Figure 11 show that the operator is able to stabilize the robot CoP and hence balance the robot. The trajectory of robot CoP remains inside of the support polygon as shown in Figure 10.

Plots 11a and 11b are the normalized time trajectories of system signals for the unexpected force disturbance on the robot. The signs of the signals are matched for ease of comparison. 11c show the results in which the human operator could anticipate the impact disturbance with a countdown.

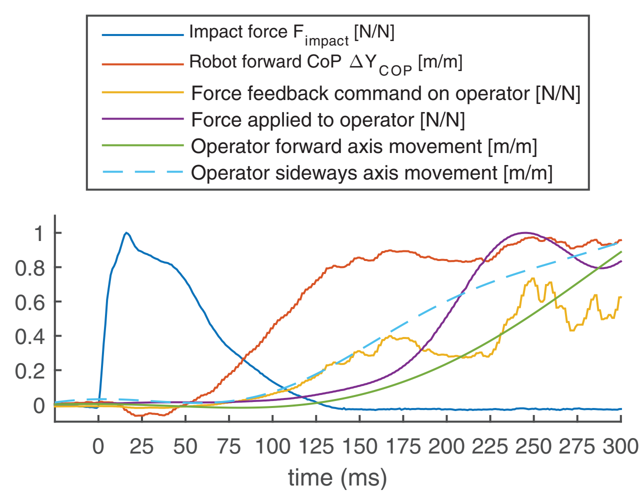
The human operator strategy can be seen in the time trajectory of operator movement over 4 seconds after the



(a) Unexpected impact disturbance on robot



(b) Unexpected impact disturbance on robot zoomed in to show the propagation of signals through the system



(c) Expected impact disturbance on robot

Fig. 11. Time trajectory of multiple signals during a impact disturbance on the robot. Signals are normalized and bias is removed to aid in visualizing the propagation of information.

impact disturbance in Figure 11a. This strategy emerged over several hours of testing during the development of the system. During the initial rise in feedback force, the operator's hips comply to the feedback force, which commands the robot to tilt the torso at the hips. However, after the force falls from its peak, the operator maintains a smooth transition back to equilibrium and allows the robot CoP oscillations to damp out. Notice that although the robot CoP oscillates around the new equilibrium after 1.5 seconds, the force feedback command to the operator is minimal because the robot CoP is moving in a safe zone.

Figure 11b shows the onset of change in signals of the system feedback loop and gives insight into the maximum performance of the balance feedback system. The results are compiled in Table II. The 50 ms delay between the initial impact and the movement of the robot CoP is a fixed property of the humanoid hardware dynamics. We expect the maximum delay between actuator movements and change in CoP to be similar. The movement of the robot CoP generates a force feedback command on the operator but the due to the bandwidth of the actuators on the Balance Feedback Interface, there is a delay of 55 ms before the force is applied to the operator. The operator hip movement in the forward axis matches the applied force. Since the shortest typical human proprioceptive reflex response time in the literature is about 50 ms, this suggests that the initial operator movement is due to passive compliance. The operator is holding a position with a given stiffness. Although the experiment was conducted using the forward movements of the robot and operator, the operator's sideways movement can provide insight on the human response. The operator shows sideways movement 50 ms after the force is applied which matches reflex times in literature. We hypothesize that since it is unlikely for a human to move perfectly in a single axis, that the sideways movement captures the delay of the operator's active response to the feedback force. Therefore the system is lower bounded by 100 ms of fixed delay due to the robot and human operator dynamics.

Two delays between the change in robot CoP to the actual feedback force on the operator's waist are flexible. The 20 ms delay between movement of the robot CoP and rise in the force feedback reference command on the operator is due to the neutral zone of the robot's CoP in which nearly no force is commanded. Only when the robot CoP nears the edge of the support polygon, does the force feedback rapidly increase in magnitude. A controller that incorporates the CoM velocity would be able to predict the trajectory of the CoP and possibly command a feedback force on the operator earlier. The 55 ms delay between the force feedback command on the operator and the actual force is due to the bandwidth of the Balance Feedback Interface. With higher bandwidth actuators and control, this delay can be drastically reduced.

Figure 11c for the experiment in which the operator anticipated the impact disturbance show largely the same delays as the unexpected impact with one striking difference. The sideways movement of the human operator which

TABLE II

ONSET OF SIGNAL CHANGE FOR UNEXPECTED IMPACT AT TIME T

Impact force	T + 0 ms
Robot CoP	T + 50 ms
Force feedback command on operator	T + 70 ms
Force applied to operator	T + 125 ms
Operator hip movement	T + 125 ms
Operator active response	T + 175 ms

commands the robot posture precedes the actual feedback force on the operator by 50 ms probably due to the audible countdown. The forward movement of the operator matches the applied force. This suggests that the human operator was able to prepare its body for the force feedback. With some combination of feedforward through either force feedback or other sensory input, it may be possible to reduce the loop delay and increase performance in dynamic tasks.

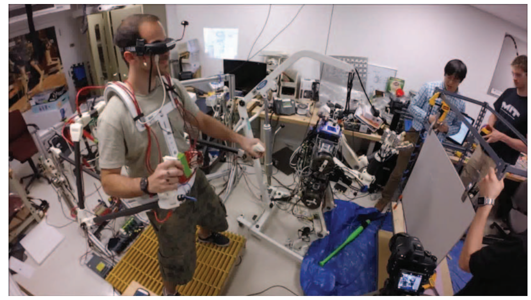
C. High Force Dynamic Wall-breaking Task

A demo that highlights the integration of human cognition and motor skills to teleoperate the HERMES robot is breaking through drywall. This is a task that cannot be achieved with high force for humanoid robots that attempt to maintain static balance throughout the motion. In order to apply a large force, the robot must find a way to anchor itself or use the body momentum to apply impact force. The sequence in Figure 12 shows a strategy that is possible with whole body teleoperation and balance feedback. First, the operator uses the onboard camera to identify an object that can be used to anchor the body and holds onto it with one hand. Second, the operator commands the robot to pull on the anchored arm to create forward momentum towards the wall. Simultaneously, the operator commands a punch using the closed fist of the opposite arm. Finally, after the robot has successfully broken through the wall, the operator uses the arms to push off the wall frame to regain balance. The operator is aware of the balance of the robot through force feedback from the Balance Feedback Interface and can creatively use many strategies involving a mix of upper and lower body posture to regain balance. The accompanying video shows wall breaking as well as other capabilities.

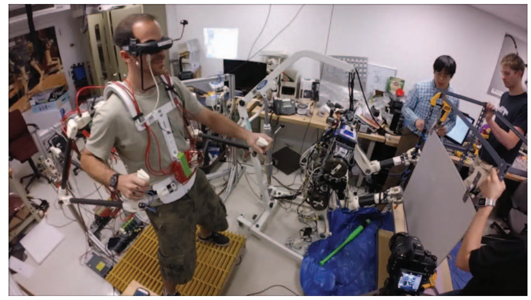
V. CONCLUSION

This is an introductory study of full body teleoperation with human-in-the-loop balance feedback. This paper shows the system design considerations and initial experiments show that human operator is able to stabilize the robot CoP after an impact disturbance. In addition, the advantages of using innate human strategies for dynamic movements are demonstrated in a wall-breaking task.

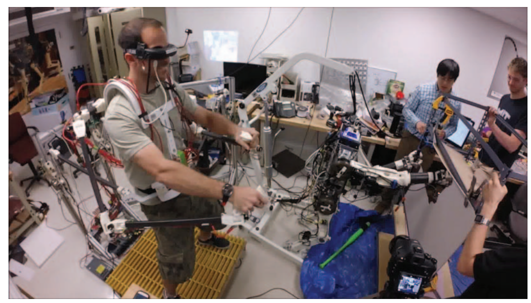
The experiment in which an impact disturbance was applied to the humanoid robot, and loop dynamics were recorded show that the humanoid and the human operator account for 50 ms each of delay, giving a performance bound of the system of 100 ms. The 175 ms of total system loop delay was found to be sufficient for controlling robot balance but in ideal situation, this should be minimized. We plan to



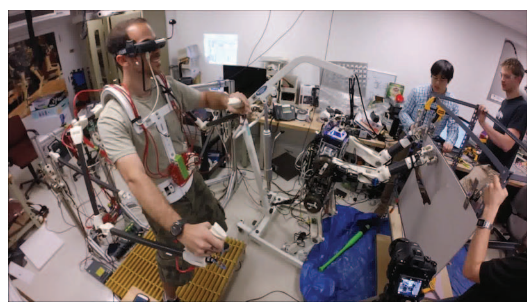
(a) Starting position



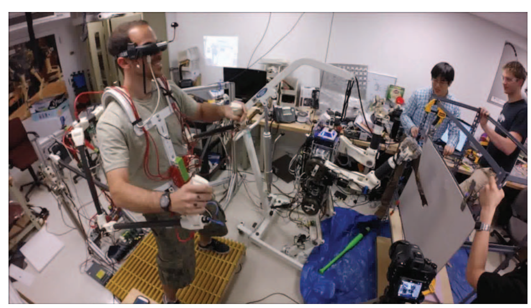
(b) Operator commands the robot to grab the frame



(c) Operator commands a punch



(d) Robot pushes off the wall with balance feedback on



(e) Operator restabilizes the robot with balance feedback

Fig. 12. Sequence showing the HERMES system breaking through a wall. The safety ropes on humanoid are loose

improve the feedback mechanism to reduce delay due to the CoP to operator force mapping and force production in the Balance Feedback Interface. In addition, we intend to explore feedforward methods to use human anticipatory control.

The ultimate solution for humanoid teleoperation likely involves human creativity as well as high speed autonomus control. Future work will explore alternate methods of balance feedback through different mapping functions or placement of feedback elements on the operator's body. Legs will be added to motion capture suit to allow operator control of stepping. Finally, common human control strategies will be observed by the human motion capture device to better predict human intention and autonomously execute learned strategies.

VI. ACKNOWLEDGMENTS

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