2015 IEEE-RAS 15th International Conference on Humanoid Robots (Humanoids)
November 3 - 5, 2015, Seoul, Korea

A Balance Feedback Interface for Whole-Body Teleoperation of a Humanoid Robot and Implementation in the HERMES System

Joao Ramos[1], Albert Wang[1], Wyatt Ubellacker[1], John Mayo[1], and Sangbae Kim[1]

***Abstract*— This paper presents the concept, design, and experimental implementation of a Balance Feedback Interface (BFI) for human-in-the-loop control of a humanoid robot. The purpose of the BFI is to create a new media to aid the task of bilateral feedback during full-body teleoperation of humanoid robots. It explores human's primitive motor skills to enhance the dynamic behavior of the slave platform to a performance level comparable to humans. This project aims to leverage legged robot's performance to respond to disaster situations such as nuclear, fire, or chemical hazards. We expect to reliably deploy a legged platform to a dangerous environments and perform powerful manipulation tasks such as hammering/axing, moving/lifting heavy objects, etc. Initial results show that the human can react to disturbances on the humanoid robot while performing an upright balancing task. We believe this is the key technology that allows for the paradigm shift from quasi-static regime to truly dynamic performance of humanoid robots.**

I. Introduction

Recent results presented at the DARPA Robotics Challenge (DRC) in the beginning of June 2015 showed that state-of-the-art autonomous control of legged platforms is far from humans' dynamic motor performance [1]. The majority, if not all, behaviors presented at the competition were quasi-static and very slow, the robots struggled to perform task that can be easily carried out by a person, like walking or balancing while opening a spring-loaded door.

In order to tackle various disaster situations, the robotic platforms should be able to reliably perform high power dynamic tasks such as hammering, pushing/lifting heavy objects, opening a spring-loaded door, jumping; tasks that are extremely basic for humans. These tasks require more than a stabilization algorithm since it requires dynamic shift of center of mass to generate higher forces in an upright posture. In many cases, we have to exploit destabilizing actions to generate momentum to perform high force manipulation. We hypothesize that if the operator can have access to the balance information of the robot in a very intuitive way, he can learn how to perform dynamic tasks such as opening a spring-loaded door utilizing momentum shift of the body.

Previously several groups have developed strategies to perform whole-body teleoperation and coordinate all of the degrees of freedom (DOF) of the humanoid platform. But usually this task is carried out by uni-directional control, when the operator sends postural position-based commands to the robot. Conventional strategies to translate the operator's intent is to utilize camera-based Motion Capture (MoCap) systems to track the user's movements [2], [3], but this introduces large time delays due to imaging processing and also have problems with limb occlusion. Other approaches track the user's end-effector position (hands/feet) and map those coordinates to robot joint position [4]. On the other hand, the work at [5] utilizes a scale marionette of the robot that the operator can freely move, and this motion is scaled to robot joint coordinates; this strategy would be impractical for dynamic coordinated motions. The user relies on cameras and similar visual/audio inputs to compensate for external disturbances and would be unaware if the robots starts to tilt or even fall. Some teleoperation devices such as the one in [6] use haptic feedback to inform to the user about forces applied to the robot end-effectors. In these approaches, the user is uninformed of any whole-body disturbances on the robot. An exception to these examples is to inform the distance from the robot's CoP to the edge of the support polygon using vibrotactile actuators attached to the operator's torso [7]. The disadvantage of this approach is the human low resolution interpreting the vibration

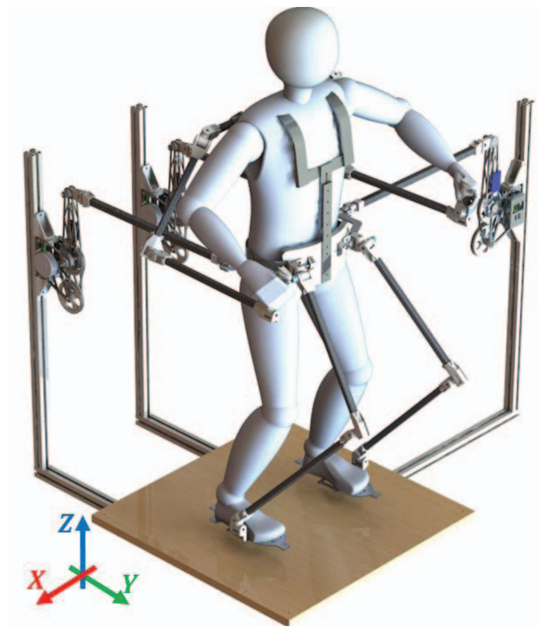

Figure 1: The Balance Feedback Interface and the Mechanical Motion Capture Suit.

*This research is funded by DARPA Young Faculty Award.

1 Authors are the Biomimetic Robotics Lab, Mechanical Engineering Department, Massachusetts Institute of Technology, Cambridge, MA, 02139 USA (corresponding author: jlramos@mit.edu).

978-1-4799-6885-5/15/$31.00 ©2015 IEEE

input and potential difficulty to use in highly dynamic situations.

In order to develop intuitive, low latency and non-intrusive Human-Machine Interface (HMI), we chose to use proprioception feedback although humans rely on three sensory inputs for balance feedback: proprioceptive, vestibular and visual [8]. We assume that galvanic vestibular stimulation or visual feedbacks are not appropriate for this application since because these two approaches can be intrusive, slow, and potentially not intuitive. It is known that proprioceptive feedback can be inherently faster than vision-based reactions (50-100ms compared to 150-250ms) [9] and triggers true balancing and reactive motions that are the primitive of human motor control.

This work presents our approach to close the missing gap between human and robot for full-body teleoperation. We aim to develop a Balance Feedback Interface (BFI) for human-machine interaction that relies on the operator's proprioceptive input and fast reflex-based response to achieve dynamic whole-body motion for humanoid robots. To achieve this bilateral feedback control loop we use the distance of the robot's Center of Pressure (CoP) to the edge of the support polygon as a metric for stability [10]. This information is accordingly mapped into forces that are applied to the operator's waist and allows the human to be aware of the robot's "state of balance". With this strategy we expect that the operator can rapidly update the robot commanded posture in order to successfully complete the ongoing task. This solution improves the situational awareness in supervisory control and reaches a new level of dynamic synergy between man and machine. The device is shown in Fig. 1.The proposed BFI is implemented in a human-in-the-loop architecture to teleoperate HERMES, a humanoid robotic platform designed to achieve power manipulation shown on Fig. 2. Details for this platform are described at the companion paper [11]. The 45kg anthropomorphic robot have six DOF limbs and share the same actuator technology as the MIT Cheetah 2 [12]. It has about 90% scale of the average male human in order to comfortably interact in environments originally designed for humans.

Finally, the Balance Feedback Interface shows a potential for use in human motion planning studies, when precise and repeatable disturbances can be applied to the evaluated subject. The responses can be easily captured and used to formulate a motor control strategy that can be either implemented on a robotics platform or used to extract principles of human motions.

This paper is organized as follows. Section II presents some design principles that are the key for the development of the BFI and the MoCap suit. Section III presents the control strategy used for the force controller and also the mapping between CoP and body force and also the kinematic mapping between robot and operator. Section IV presents experimental results for different disturbances while maintaining balance and section V concludes with relevant aspect about the system behavior and limitations. Finally, section VI introduces future applications for the Human-Machine Interface (HMI) and possible strategies for improving the whole-body controller.

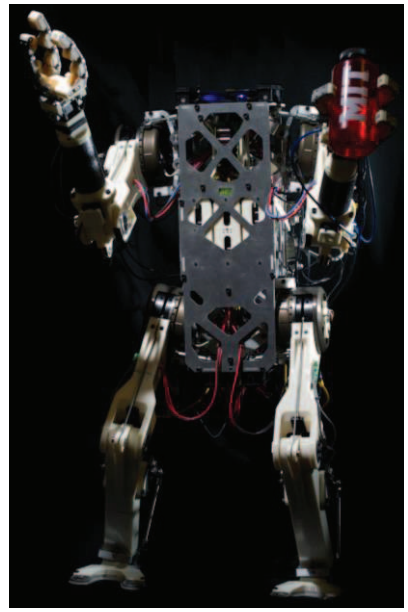

Figure 2: The HERMES humanoid robotic platform for power manipulation and highly dynamic behavior.

II. Major Design Principles

The proposed Human-Machine Interface (HMI) is shown on Fig. 1. The master system is composed of the Balance Feedback Interface (BFI) and a low latency mechanical Motion Capture (MoCap) suit. The forces are applied near the user's Center of Mass (CoM) and we expect that this disturbance triggers the correct motor reflex. Furthermore, it is required from the BFI to be transparent to the user (backdrivable and low inertia, be nonintrusive, be instinctive (reflex-based), and use no visual or audio input.

Inspired by the promising results from the previous device at [15], the current BFI allows unconstrained motion of the user's hip in six degrees of freedom (DOF), an important feature to achieve highly dynamic behaviors. Three actuators can generate three axis of forces/torques on the human according to the state of the slave robotic platform. Also, a force plate records the motion of the user's Center of Pressure (CoP) using four load cells.

There are many commercial systems available for human tracking, including mechanical suits, inertial measurement unit (IMU) suits, and a variety of optical tracking systems. Most mechanical suits measure the joint angles directly, and offer fast acquisition times (often above kHz sample rates) and noiseless measurements using encoders, but have very poor range of motion and must be correctly sized for each individual. Some inaccuracy may be introduced if the body attachment points are not rigid, as is usually the case with the skin of the human. IMU suits offer flexibility in operator dimensions and good range of motion, but suffer from low sample rates (~200Hz), low resolution (~0.5 degrees) [13], and noise due to gyroscopic drift, magnetic interference, and mechanical noise from the compliant suit and body of the human. Optical systems provide the best range of motion, and if enough cameras and markers are used, the problems of occlusion and measurement noise can be filtered out. However, the acquisition time is limited by both the frame rate of the cameras (360 Hz for high end systems) [14] and the image post-processing time (an additional 8-10ms in our experiments). With these limitation in mind, we developed a large range of motion, lightweight and low latency mechanical MoCap for full-body tracking.

A. BFI Motor Modules

Each of the BFI arms is a 3DOF modular underactuated manipulator as shown on Fig. 3. The blue arrows represent the axis on which each joint rotates. Joint angles are measured using 12-bits *Avago Technologies* absolute magnetic encoders. The first and third joints are passive while the middle one is actuated by a *48V EC90 Flat Maxon Motor* under torque control.

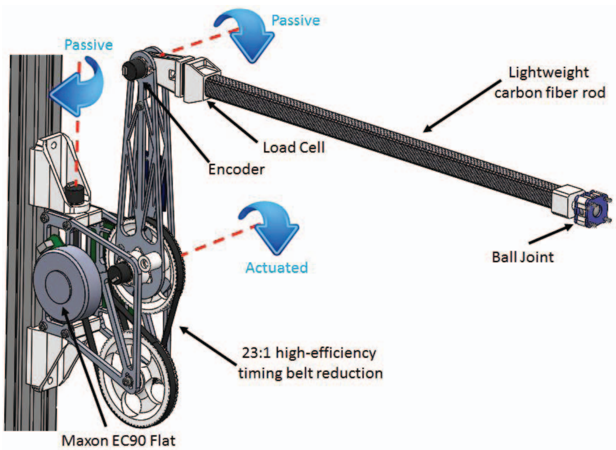

Figure 3: BFI modular 3DOF underactuated manipulator. The blue arrows indicate the rotary joint around the red dotted axis.

Each module can generate continuous forces F_i up to 50N on the direction of Link 3 when the motor applies a torque τ_i, as shown on Fig. 4. All applied forces are monitored by *25lb Transducer Technologies* load cells in line with the third link. In parallel all three actuators can generate forces and torque on the user's transverse plane. Notice that the third link is longer in order to mitigate the effect of the forces on the vertical direction for a given vertical displacement. Also, all the link inertias are minimized to improve bandwidth and backdrivebility.

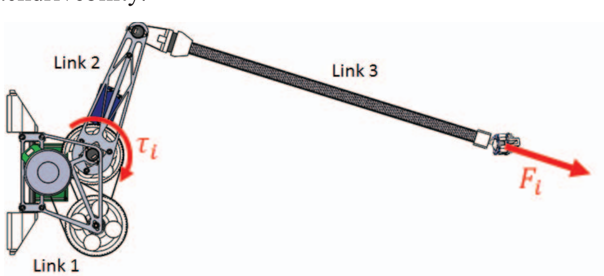

Figure 4: Force generated by each module.

B. Parallel Actuation

Together, the three underactuated manipulators apply forces on the operator's waist. The end-effector of the complete parallel actuation system has three passive and three active DOFs as show in Fig. 5. Together F_2 and F_3 can produce forces in the Y direction and a torque about Z, while F_1 generates force in the X axis. This end-effector is unconstrained in all six axes. Notice that link 3 of module 1 is curved in order to clear the left upper limb of the user, but the direction of the generated force is similar to the other modules.

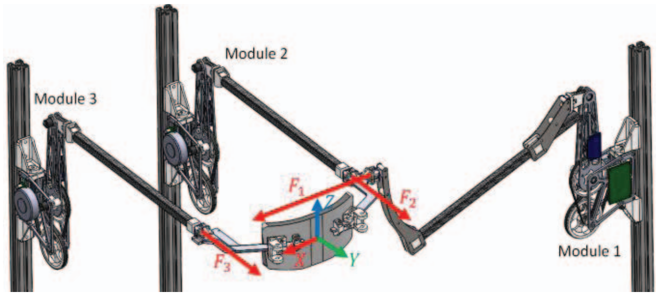

Figure 5: BFI parallel actuation design.

The forces applied on the user's waist can be calculated using

$$\vec{F} = \sum_{i=1}^{3} F_i . \vec{u}_i, \tag{1}$$

$$\vec{M} = \sum_{i=1}^{3} F_i . (\vec{r}_i \times \vec{u}_i) \tag{2}$$

where $\vec{F}$ and $\vec{M}$ are the 3x1 vectors of forces and moments applied to the user's waist; $\vec{u}_i$ is the unit direction vector of the force F_i produced by manipulator i; and $\vec{r}_i$ is the radial distance between the origin of frame fixed to the end-effector and the point of actuation of force F_i.

Given the desired force and moments $\vec{\tau}_R = [F_x \quad F_y \quad M_z]^T$ to be applied to the human, equations (1) and (2) can be used to solve for forces F_i and these results generate desired torques τ_i with the inverse kinematics. Notice that this architecture produces residual force and torques F_z, M_x, and M_y. But these effects are negligible to the user due to the length of Link 3.

C. Motion Capture Suit

The human body is a complex structure, with multi-DOF joints capable of a wide range of motion and near-continuous structures like the spine. However, the HERMES humanoid robot has a much more limited range, and the human DOF can be constrained or omitted in order to simplify the device design.

The suit uses a modified commercial harness attached at the hips and shoulders, the most rigid part on the torso (see Fig. 6). The harness also serves to lock the spine, and constrain motions from the human torso that the robot does not possess. The suit limbs are six DOF passive manipulators that connect from near the human torso (hip and shoulder) to the end-effector (feet and hands). The linkage geometry gives sufficient range of motion to the human (to accommodate up to 99th percentile for height), avoiding singularities and selfcollisions. In order to minimize inertial effects during dynamic motions the suit limbs are lightweight square carbon fiber rods with small ABS plastic joints. Each joint has a 12-bit absolute encoder which are read in parallel at 10 kHz sampling rate using an FPGA. The forward kinematics are calculated to determine the actual end-effector position from the suit joints angles. This leads to an overall minimum accuracy of about 1.5 mm and an acquisition time of 400µs (2.5 kHz).

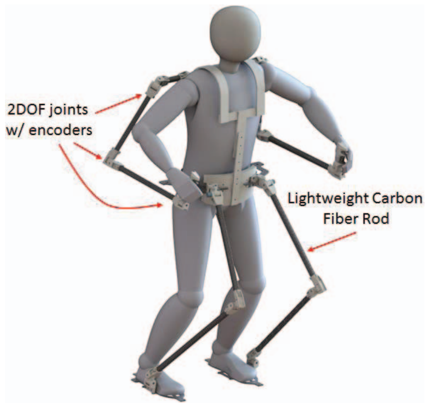

Figure 6: Low latency full-body MoCap.

III. Planning and Control

During teleoperation, the robot slave follows postural position based commands given by the human through the MoCap suit. As the robot moves, the CoP translates and the human is perturbed accordingly. Each manipulator then applies up to 50N of force at the user's waist, which is monitored by the in line load cells. The reference force is generated using the robot's support polygon and CoP in order to transmit to the human the state of balance of the robotic platform.

The BFI and MoCap are controlled with a *National Instruments cRIO-9082 FPGA* real-time computer.

A. Human Motion Mapping

An integral part of the control loop for the human-robot interaction is measuring the posture of the pilot. There are two general ways to define the pose of the human: using joints angles of each joint, or the Cartesian position and orientation of the end effector. As the MoCap doesn't perfectly match the user's limb geometry and kinematics some mapping is required to translate human pose into robot pose.

The mapping translates human end-effector position to a proportional robot end-effector position, scaled according to the user's height and limb length:

$$X_{H_i} = \alpha . X_{R_i}. \tag{3}$$

Where X_{H_i} and X_{R_i} are human and robot end-effector Cartesian coordinates for limb i, and α is a scaling constant. The same strategy is used for hip mapping. The lower limbs of the MoCap are not used in this study, instead the robot follows the same torso orientation as the operator, similar to the mapping utilized on [15].

B. Center of Pressure to Force Mapping

The reference force to be applied at the operator's waist varies according to the robot CoP position. According to [9] the robot can balance and stay upright if its own CoP remains inside support polygon. This polygon is given by the convex hull that include all contact points of the robot with the ground. As shown on [11], HERMES has three load cells under each foot and it is assumed that these are the only possible contact points with the ground at all times. Thus, the convex hull can include from one to six points.

In order to transmit to the human the disturbances on the robot, the force generated by the BFI increases as the CoP approaches the edge of the support polygon. As shown on Fig. 7, the geometry of the polygon can vary according to the robot posture and dynamics. The CoP relative planar coordinates can be directly measured using the feet load cells. Given these two measurements, the distance d_i from CoP to each edge and also the unit direction $\vec{v_i}$ can be estimated (on the figure only v_4 is shown in order to avoid clustering).

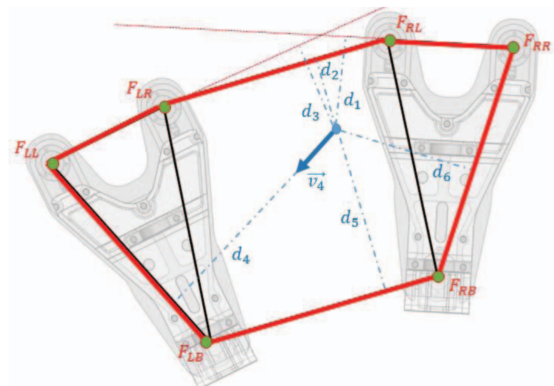

Figure 7: The blue dot represent the robot's CoP translates as the robot moves. The green dots represent the contact points of the feet and the red polygon shown the robot support.

The force applied to the human is calculated using

$$\overrightarrow{F_R} = -K_p \sum_{i=1}^{N} \frac{1}{d_i} \vec{v_i} - Kd.\,\omega_{pitch}. \tag{4}$$

Notice the negative sign indicates that the force applied to the human informs in which direction the user should move in order to allow the robot to regain balance. To damp out fast reflexed-based commands we utilize a second term that takes into account the torso pitch angular speed. Fig. 8 shows the force gradient for locations inside the boundaries of the support polygon for $\omega_{pitch} = 0\ rad/s$.

C. BFI Force Controller

The BFI force controller is composed of a feedforward path and a low gain feedback path as shown on Fig. 9. The feedforward path uses the device model to directly input the reference torque to the motor current controller, the feedback path, on the other hand takes care of additional errors and system losses. The force closed-loop controller presents a rise time of about 40-50ms.

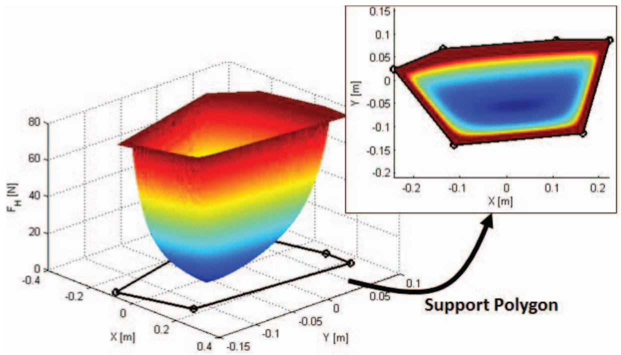

Figure 8: Force field utilized for balance feedback mapping.

The force controller runs on the real-time computer at a 2.5kHz loop rate.

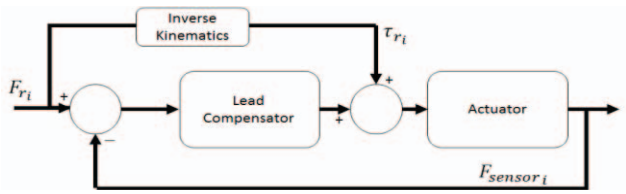

Figure 9: Force controller block diagram.

IV. Experimental Results

The conducted experiments have the objective of evaluating the proposed BFI and force mapping strategy as an universal media to inform the operator about the robot balance state. The source of disturbance on the robot can vary greatly: external forces, self-inducted inertial forces, gravity, etc. Thus, in order to verify the performance of the system three experiments are proposed: (i) external impulsive force applied to the robot's torso; (ii) self-induced dynamic loads; and (iii) sensitivity to limb inertia variation (holding payload).

As presented on the previous section, when the robots is disturbed by the environment and the CoP shifts, forces are applied to the operator's waist accordingly. We expect that the robot's state of balance can be transmitted to the human using this minimal input, avoiding complexity and ambiguous information. As a result, the user can take counter measures to regain stability.

Fig. 11 and 12 show the robots behavior on each test. Notice on Fig. 11 the variation on the absolute force F_y applied to the human as the robot's CoP translates inside the support polygon. The green dashed lines indicates the edge of this support. Hysteresis is present in all cases as the CoP shifts back to a safe region (see trajectory arrow) and may be mitigated by increasing feedback gain in the force control. Fig. 12 presents the planar motion of the robot's CoP inside the convex hull of the support polygon as the machine reacts to the disturbances.

Notice in all three types of disturbances, the dynamics occur in the sequence shown on the schematic in Fig. 13. The disturbance shifts the robot's CoP, which is mapped into force on the operator, who readjust its own posture and thus updates the robot's posture. The companion paper [11] presents an in-depth temporal analysis of the system dynamic behavior.

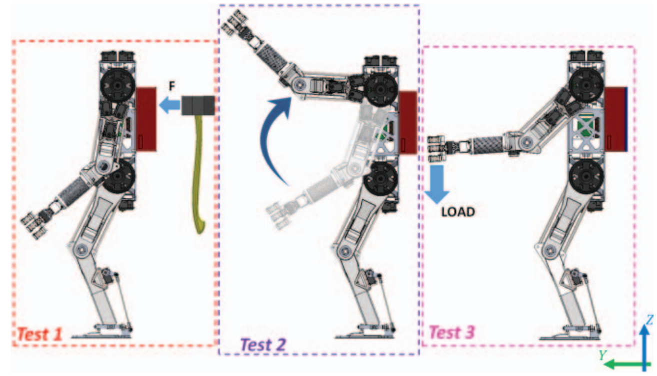

Figure 10: Left: external impact disturbance; center: self-induced disturbance; right: disturbance due to payload manipulation.

A. Test 1: Impact Forces

The first experiments evaluated the robot behavior under impact disturbances from a rubber axe as show on Fig. 10 left. On Fig.14, the non-dimensional blue peak indicates the moment when the rubber hammer hits the robot from the back. The CoP shifts forward and a force is applied to the human. For the sake of comparison all plots on Fig. 14 to 16 are normalized and the bias is removed. Peak force applied to the human F_y is about -65N.

In this case the robot's CoP shoots to a dangerous position and is later compensated by the human action. The operator is actually made aware of the event and actively readjust the posture, driving the CoP back to a safe zone.

B. Test 2: Explosive Motions

The second test evaluated the system response to explosive motions such as a fast arm swing, see Fig. 10 center. The shoulder angle varies about 33^0 in a 610ms pulse, see Fig. 15. Peak force applied to the human F_y is about -36N.

Different from the previous test, the rapid arm motion is translated to an almost instantaneous change on the robot CoP and an equivalent impulsive force on the human. As the arm returns to the original position the CoP oscillates back to the starting position and the operator is passive to the disturbance. The CoP is translate for about only 300ms and although the operator is made aware of the disturbance, it is unlikely that he can react in time to compensate it.

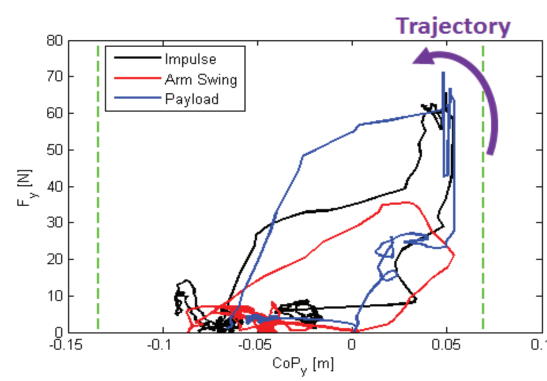

Figure 11: CoP trajectory on sagittal plane during three tests. Notice the green dashed lines indicate the two extremes of the support polygon.

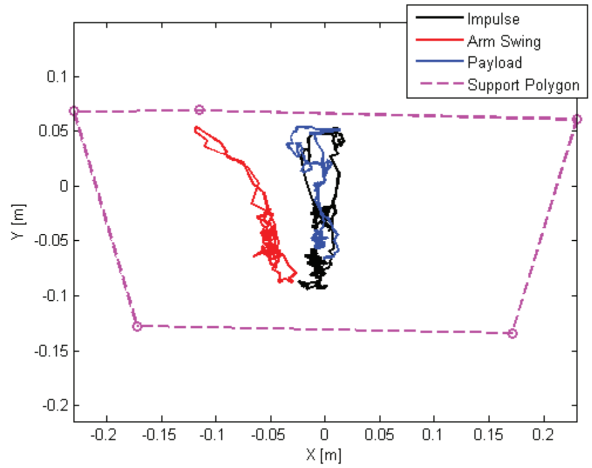

Figure 12: CoP trajectory planar during tests. Notice the pink dashed lines indicate the support polygon.

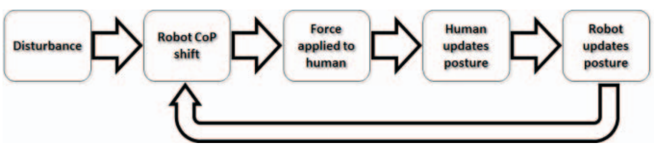

Figure 13: System chain of dynamic events for reactive motion.

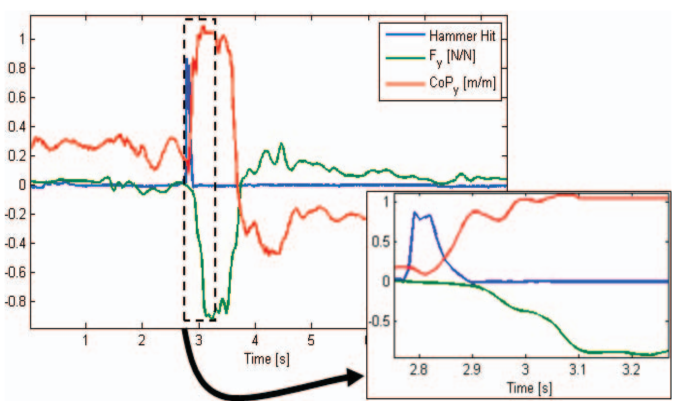

Figure 14: Robot dynamics under impact disturbance.

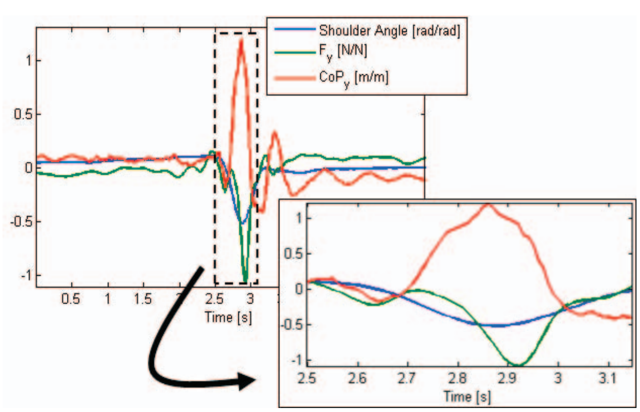

Figure 15: Robot dynamics under arm swing.

C. *Test 3: Limb Mass Variation*

Finally, we evaluate the system response when a payload is held by the robot, see Fig. 10 right. A 1.2kg (2.7lb) and a 2.8kg (6.2lb) payload are placed at the robot's hand at distance of approximately 680mm (26.8") from the shoulder. Fig. 16 shows the robot's CoP shifts to different equilibrium position after the oscillation for each of the weights. Peak force applied to the human F_y are -21N and -70N.

The smaller weights represents a small disturbance on the robot's CoP and the force applied to the human is proportionally small, resulting in a subtle postural reaction. A more drastic motion is observed for the larger weight, with also some oscillation. The payload which results in a long term change in limb mass properties is effectively zeroed out by the operator without knowledge or dynamic model of the robot or the load.

V. Conclusion

A Human-Machine Interface for bilateral feedback during humanoid robot teleoperation is presented and evaluated. The proposed device explores the strategy of transmitting to the human operator the state of balance of the robot in order to exploit inherent human motor skills which aids in the robot's task. Beyond legged balancing, which can be easily achieved by conventional autonomous controllers, the BFI shows potential to be a universal feedback device to display a wide range of disturbances.

The proposed methodology was evaluated for three different disturbances while maintaining a stable upright posture. The results suggest that the CoP to force mapping triggers very intuitive behaviors and the user can successfully react to the disturbances applied to the robot. It is relevant to point out that the user is able to interact with the robot without any prior knowledge of the system dynamic behavior or any kind of visual/audio input.

All three disturbances are presented to the human operator using the same methodology and device. This results suggest that the any disturbance that is sufficient to throw the robotic platform off balance can be felt and/or compensated by the human although they come from different sources and have diverse time-variant profiles.

VI. Future Work

The intent of the Human-Machine Interface presented in this work is to aid the teleoperation task and exploit human's innate creativity in order to achieve highly dynamic behaviors on legged systems. We understand that the ultimate solution will most likely involve a hybrid control law with an autonomous behavior that negotiates with commands given by the user. With the present study we hope to study how far human motor skills can improve robots performance while interacting with disaster environments.

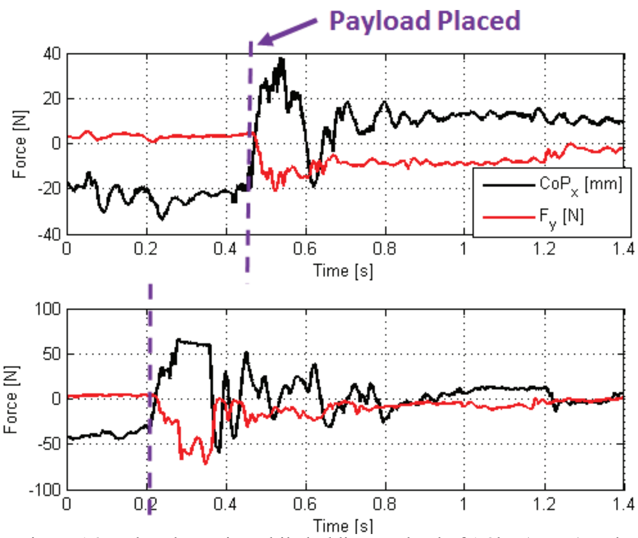

Figure 16: Robot dynamics while holding payload of 1.2kg (upper) and 2.8kg (bottom).

It's still unclear how much aid the reflex-based reactions from humans can improve robot motion and what is the best strategy to synchronize both systems. Further studies will be conducted regarding utilizing negative feedback on the human. Different from the current work, this control law would apply forces on the human waist in the same direction of the disturbances and the human behaves as an active controller instead of a mechanical filter. It is expected this response time to be slower due to the fact that it depends on human reactive time to control the robot.

VII. Acknowledgments

This work is funded by DARPA Young Faculty Award.

References

[1] The Robotics Challenge: http://www.theroboticschallenge.org/

[2] S. K. Kim, S. Hong, D. Kim, "*A Walking Motion Imitation Framework of a Humanoid Robot by Human Walking Recognition from IMU Motion Data*", in *Humanoid Robots, 9th IEEE/RAS International Conference on*, IEEE, 2009.

[3] J. Koenemann, F. Burget, M. Bennewitz, "*Real-time Imitation of Human Whole-Body Motions by Humanoids*", in *Robotics and Automation (ICRA), 2014 IEEE International Conference on*, 2014.

[4] E. Neo, K. Yokoi, S. Kajita, K. Tanie, "*Whole-Body Motion Generation Integrating Operator's Intention and Robot's Autonomy in Controlling Humanoid Robots*", IEEE Trans. On Robotics, Vol., 23, No. 4, 2007.

[5] T. Takubo, K. Inoue, T. Arai,. "*Whole-body Teleoperation for Humanoid Robot by Marionette System*", in *Intelligent Robots and Systems (IROS) 2006 IEEE/RSJ International Conference on*. IEEE, 2006.

[6] R. Chipalkatty, H. Daepp, M. Egerstedt, "*Human-in-the-Loop: MPC for Shared Control of a Quadruped Rescue Robot*", in *Intelligent Robots and Systems (IROS) 2011 IEEE/RSJ International Conference on*. IEEE, 2011.

[7] Brygo, A, Sarakoglou, I., Garcia-Hernandez, N., and Tsagarakis, N., "*Humanoid Robot Teleoperation with Vibrotactile Based Balancing Feedback*", Italian Institute of Technology, Genova, Italy

[8] S. Anderson, C. Atkeson, A. Mahboobin, P. Loughlin, M. Redfern, "*Sensory Adaptation in Human Balance Control: Lessons for*

[9] E. Burdet, D. W. Franklin, T. E. Milner – *Human Robotics: Neuromechanics and Motor Control*, The MIT Press, 2013. *Biomimetic Robotic Bipeds*", Carnegie Mellon University Robotics Insittute, Research Showcase @ CMU, 2008.

[10] M. Vukobratovic, B. Borovac, "*Zero-Moment Point – Thirty Five Years of its Life*", Internatonal Journal of Humanoid Robotics, Vol. 1, No. 1, pp157-173, 2004.

[11] A. Wang, J. Ramos, J. Mayo, W. Ubellacker, and S. Kim, "*The HERMES Humanoid System: A Platform for Full-body Teleoperation with Balance Feedback*", in *Humanoid Robots, 2015 15th IEEE-RAS International Conference on*. IEEE, 2015 (submitted).

[12] S. Seok, A. Wang, M. Y. Chuah, D. Otten, J. Lang, S. Kim, "*Design Principles for Highly Efficient Quadrupeds and Implementation on the MIT Cheetah Robot*", in *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, 2013.

[13] Vectornav Embedded Navigation Solutions, http://vectornav.com/

[14] Optitrack Motion Capture Systems, http:// optitrack.com/

[15] J. Ramos, A. Wang, and S. Kim, "*A Balance Feedback Human Machine Interface for Humanoid Teleoperation in Dynamic Tasks*", in *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on*., IEEE, 2015, (accepted).

[16] K. Kuchenbecker, N. Gurari, Al. Okamura, "*Effects of Visual and Proprioceptive Motion Feedback on Human Control Targeted Movement*", in *Rehabilitation Robotics, 2007 IEEE 10th International Conference on.* IEEE, 2007.

[17] D. Orin, A. Goswami, S. Lee, "*Centroidal Dynamics of a Humanoid Robot*", Journal on Autonomous Robots, Vol. 35, Issue 2-3, pp. 161-167, 2013.

[18] S. Yun, A. Goswami, "*Momentum-Based Reactive Stepping Controller on Level and Non-Level Ground for Humanoid Robot Push Recovery*", in *Intelligent Robots and Systems (IROS) 2011 IEEE/RSJ International Conference on*. IEEE, 2011.

[19] M. Lakie, D. Loram, "*Manually Controlled Human Balancing Using Visual, Vestibular and Proprioceptive Senses Involves a Common, Low Frequency Neural Process*", J. Physiology, 577.1, 33. 403-416, 2006.

[20] S. Nakaoka, A. Nakazawa, F. Kanehiro, K. Kaneko, M. Morisawa, K. Itekeuchi, "*Task Model of Lower Body Motion for Biped Humanoid to Imitate Human Dances*", in *Intelligent Robots and Systems (IROS) 2005 IEEE/RSJ International Conference on*. IEEE, pp 3157-3162, 2005.

[21] S. Kim, C. Kim, B. You, S. Oh, "*Stable Whole-Body Motion Generation for Humanoid Robots to Imitate Human Motions*", in *Intelligent Robots and Systems (IROS) 2009 IEEE/RSJ International Conference on*. IEEE, 2009.

[22] J. Babic, J. Hale, E. Oztop, "*Human Sensorimotor Learning for Humanoid Robot Skill Synthesis*", Adaptive Behavior, SAGE, pp. 250-263, 2011.

[23] B. Stephens, C. Atkeson, "*Dynamic Balance Force Control for Compliant Humanoid Robots*", in *Intelligent Robots and Systems (IROS) 2010 IEEE/RSJ International Conference on*. IEEE, pp 1248-1255, 2010.

[24] K. Pipereit, O. Bock, J. L. Vercher, "*The Contribution of Proprioceptive Feedback to Sensorimotor Adaptation*", Experimental Brain Research, Springer-Verlag, Vol. 174, Issue 1, pp. 45-52, 2006.

[25] H. Daepp, W. Book, "*User Interface with Multisensory Feedback for Fluid Powered Rescue Robot*", Proceedings of the 6th FPNI – PhD Symposium, Georgia Institute of Technology, 2010.

[26] R. T. Peterka, "*Sensorimotor Integration in Human Postural Control*", J. of Physiology, 88.3, pp. 1097-118, 2002.