HUME: A Bipedal Robot for Human-Centered Hyper-Agility

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I. Introduction

Our broad goals are to understand the physical capabilities and physiology of human movement for use in the design of machines with similar abilities. Here, we discuss the development of a hyper agile bipedal robot, HUME, designed to quickly traverse rough terrains that are at the extrema of what humans can overcome on two feet. We will refer to this skill as Human-Centered Hyper-Agility (HCHA). In particular the extrema of HCHA includes free-running-like capabilities on vertical surfaces (Parkour). We aim to be the first to endow true HCHA to a human-sized bipedal robot through the following approach: (1) develop a realtime single and multicontact simulator and planner for dynamic gaits in the highly irregular terrains (HCHA), (2) from this simulation environment extract the performance parameters associated with HCHA, (3) design an actuator capable of delivering the design specifications, (4) build a human-sized bipedal robot based on the desired performance, (5) create low level controllers to deal with flexible joints and Whole-Body Compliant Controllers to track the planned center of mass, feet and posture trajectories and (6) build an irregular terrain to maneuver on and supporting mechanisms to capture precision data of the free-body movement. We believe true HCHA is a very important capability because of its direct impact in the design of human assistive devices for all terrains and the design of next generation semi-autonomous bipedal robots.

Laboratories around the world have produced outstanding designs covering many different areas of legged capabilities. For the purpose of analysis we consider robots' performances as a function of speed, agility and efficiency, where speed is the center of mass absolute velocity, agility is the complexity of traversable terrain and efficiency is the cost of transport. The reader can imagine the robots reviewed below as points in 3-D space with speed, agility and efficiency as the principle performance axes, where our target performance (HCHA) would maximize speed and agility while attempting to optimize efficiency. The first biped robot to achieve "quasi-dynamic" walking was described in [13] followed by dynamically stable robots discussed in [17]. Passive dynamic walking was introduced in [15], [16] and later, in [4], [3].

Various bipedal humanoids [6], [11], [12], [14] are skilled at mimicking humans in a variety of terrains and speeds, but as terrains become more complex their speeds decrease with respect from those of the human. Bipedal robots built for high speeds [22], [2], [29] have shown that they can cover level terrain quickly but have not been used to traverse very rough surfaces at these speeds. Series elastic actuation (SEA) [18], [23] has spurred the design of various compliant robots [20], [19], [10] capable of efficiently adapting to contact transitions, and has been extended in the form of actuators with mechanically adjustable compliance in [8], [5], [9], [7]. Although the following are quadrupeds, [21], [1] are at the frontiers of hyper agility. Both have the ability to overcome rough terrains quickly and therefore it is one of our objective to endow these capabilities in a bipedal robot.

Our work is a departure from previous designs in that we seek to reach the extrema of human movement in cluttered environments. This entails a clear understanding of hyper-agility in these environments and a strong competence in building actuators and humanoid robot mechatronics. UT-Austin has teamed up with Meka Robotics to perform the study for and delivery of a machine that can show significant advancements toward HCHA. We are aware of the new PETMAN and Atlas robots by Boston Dynamics which deliver high mechanical power and speed but their detailed architecture is uncertain to us.

The effort for achieving HCHA can obviously not be centered only around hardware design but needs to be complemented by stability planners and compliant controllers. Our efforts in foot placement planning in irregular and extreme terrains has been strong recently, with publications in [24], [25], [28]. More recently we have conducted experiments on using whole body compliant control on a mobile humanoid robot that balances discussed in our submission [27].

II. Technical Approach

Motion planning: In [24], [25], [28] we considered the problem of solving step transitions at normal human speeds on irregular terrains. For single contact phases we used inverted pendulum dynamics while for multi-contact phases we proposed the use of the multi-contact grasp matrix [26] which considers both inertial/gravitational and tension forces. Given a chosen geometric path of the center of mass (CoM), a set of planned step locations, link geometries and approximate weight specifications, we use numerical integration to determine phase curves of CoM behavior. As a first approximation we determine step transitions as the points of intersection between adjacent phase curves. For multi-contact, (1) we fit curves in the phase plane of CoM behavior that mimic human captured data, (2) we impose continuity of the curves with respect to the neighboring contact trajectories, and (3) using the multi-contact grasp matrix we check that reaction forces fall within the friction cones of the surfaces in contact. This procedure delivers stable CoM trajectories in the phase plane for the seeded goals and a set of discrete step transition points. From here we use this data to obtain the mechanical parameters such as range of joint motions, joint velocities and joint torques associated with the modeled behavior.

Parameter extraction: In this stage we extract design parameters that will be used in the design of the actuators and ultimately in the design of the overall robot. In particular we seek to obtain detailed information for the following parameters: (1) joint range of motion (2) joint angular velocities and (3) joint torques. Given the CoM dynamic trajectories generated in the motion planning stage we employ inverse kinematics to obtain joint angles, angular velocities and angular accelerations. We follow this step by deriving inverse dynamics to obtain required joint torques. To be accurate, inverse kinematics and dynamics should be derived using the Lagrangian model of the free floating robot under the forces imposed by the contact stance. For instance in [27] we described how to derive inverse kinematics of a system with such constraints and in [26] we derived the associated inverse dynamics. However for this work, we have used simplified versions of both the kinematics and dynamics that involve pinning down the feet.

The motion planning and parameter extraction stages were employed to iterate though different mechanical architectures that would enhance performance. Due to our motivation to design a bipedal robot capable of achieving HCHA, we used linkage specifications similar in size to the human. This stems from the observation that bigger robots are less safe, require powerful actuators and might be too large to operate in cluttered environments. At the same time, for smaller robots, miniaturizing actuators and computational components would pose a great challenge for deployable applications.

Mechanical and electrical hardware design: The robot is a 6 degree of freedom biped designed for interacting with human scale environments at human like speeds. To facilitate this capability, each actuator utilizes series elastic elements for high bandwidth force sensing and rugged impact tolerance. To maintain low leg mass and allow for quick maneuvers, the actuators are located as high and near the center of mass as possible. Packed into the center of the torso are the leg abduction/adduction actuators while the hip flexion/extension actuators ride just above the hip's center of rotation. This configuration keeps the knee flexion/extension actuator as the only mechanism located on the leg and thus minimizes swing inertia and provides for an overall lighter leg.

Each joint of the biped is driven by a modular series elastic actuator (SEA). The design utilizes a ball screw as the major transmission component providing an efficient high gear reduction while maintaining a low rotational inertia. The ball screw drives a set of stiff springs that decouple impacts and provide force sensing. This whole spring assembly rides along on special linear bushings that are able to auto compensate for any misalignment thereby reducing friction. For the flexion/extension joints, the SEA output is then attached to cables that drive the joint while the abduction/adduction actuators use push/pull rods to maneuver the leg.

To protect the biped and provide high resolution global orientation sensing we have designed a linear boom. The boom will restrict 3 of the 6 spacial degrees of freedom including yaw, roll, and lateral motion. It will consist of two parallel rails that run the length of the robot's range of transverse motion. Attached to each rail is a four-bar linkage that carries communication and power to the robot. An overhead gantry will guide a catch rope to stop the robot during falls and provide a hoist for aid in resetting the system. The boom system will be utilized in the first part of the project for testing locomotion in the Saggital plane. At a later stage we will seek to stabilize the robot laterally for 3-D motion using inertial sensing, visual registration and the hip's lateral degree of freedom without the need for support.

III. Comparisons with other approaches and open questions

HUME can be most closely compared to M2V2 by IHMC in the sense that both employ electric motors with a ball screw in series with an elastic element. However, our robot has half the number of degrees of freedom which reduces its mass allowing for greater agility but limiting 3-D motion capabilities.

Some of the questions concerning hardware capabilities stem from the limitations of our simulations. They include what demands will need to be met when expanding to 3-D motion and how multi-contact phases and tension forces will affect performance at both slow and fast speeds. Other hardware questions arise from the physical design such as how to implement contact sensing and how to overcome the deficiencies of point contacts.

Other issues arise in the area of modeling, planning and control. Achieving closed loop stability will be an initial issue to tackle along with adapting our models and motion planning algorithms based on HUME's physical characteristics. All of these challenges represent possible interesting discussions in the context of the topics of the conference. We also would like to discuss the unconventional technology for legged robots based on employing a spinning gyro for actuating yaw rotation. Finally, we would like to give our opinion on what environments legged robots can be useful and under what technological circumstances.

IV. Format

Oral presentation - 15 minutes.

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