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SupraPeds: Humanoid Contact-Supported Locomotion for 3D Unstructured Environments

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Abstract— **Maintaining humanoid robot stability in unstructured environments is nontrivial because robots lack human-like tactile sensing and require complex task-specific controllers to integrate information from multiple sensors. To deploy humanoid robots in cluttered and unstructured environments such as disaster sites, it is necessary to develop advanced techniques in both locomotion and control. This paper proposes to incorporate a pair of actuated smart staffs with vision and force sensing that transforms biped humanoids into tripeds or quadrupeds or more generally, SupraPeds. The concept of SuprePeds not only improves the stability of humanoid robots while traversing rough terrain but also retains the manipulation capabilities. In order to control the potentially numerous contact forces on SupraPeds, we develop a friction-consistent whole-body control framework that implements generic multi-contact control for arbitrary humanoids, which enables autonomous balancing while complying with friction constraints. The simulation results are presented to demonstrate that the proposed control framework can efficiently deal with multi-contact locomotion in 3D unstructured environments.**

I. INTRODUCTION

The challenges in deploying humanoid robots in unstructured environments are numerous, and range from being able to traverse rough terrain, integrate information from tactile, kinematic, and vision sensors, execute complex manipulation, and gracefully compensate for sensor occlusion and actuator limits. Efforts to make robots emulate humans, however, have ignored an important fact: whenever humans approach their limits, they augment their capabilities with a diverse variety of tools. Perhaps the most useful and easily adopted tool is the walking staff, which improves support, enables load redistribution to the upper body, and can also be used as a sensor to probe the stability of planned footsteps. In order to advance the primary goal of humanoid robots − emulating human capabilities −, we propose to develop smart staffs that can integrate with any humanoid robotic platform, and augment the ability to operate in unstructured environments.

In the past decades, legged robotics has witnessed developments ranging from hopping robots in the eighties [1] to walking humanoid robots at turn of the century [2]. For the recent development of humanoid robots, HUBO [3] and HRP-4 [4] are designed to be position controlled. Those robots, however, might not be well-suited for compliant motion tasks. On the other hand, Petman [5] and Atlas [6] from Boston Dynamics are recent developments for torque controlled based platform. Both are anthropomorphic robots that have demonstrated considerable strength and capabilities with potential for bipedal action in rough terrain [7].

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Fig. 1. The concept of SupraPeds enhances the stability of humanoid robots in unstructured environments

Compared to biped robots, quadruped robots have been developed to signicantly improve the stability, and allowing robot deployments in even more challenging outdoor terrain. The robot LittleDog was developed to pursue research on locomotion under DARPAs Learning Locomotion(L^2) project [8][9][10], and its scaled-up version, BigDog, already demonstrated excellent balancing capabilities in rough terrain [7][11].

Unlike large quadrupeds, humanoid robots have potential to use human-scale furniture, ladders, vehicles, etc. However, despite some impressive accomplishments in terms of dynamically stable locomotion [12][13][3][14], they cannot negotiate the kinds of terrain that either humans or robots like quadrupeds can. This paper aims to address this limitation by providing humanoids with a relatively light and simple but highly effective aid for locomotion and exploration while retaining manipulation capabilities not available to quadrupeds.

The proposed SupraPed platform includes a set of smart staffs, a suite of multi-contact algorithms and control primitives, and a haptic tele-operation system that transforms biped humanoid robots into SupraPeds, tripeds or quadrupeds. Quadrupeds surpass bipeds in distributing their weight over more actuators and thus increasing their payload.

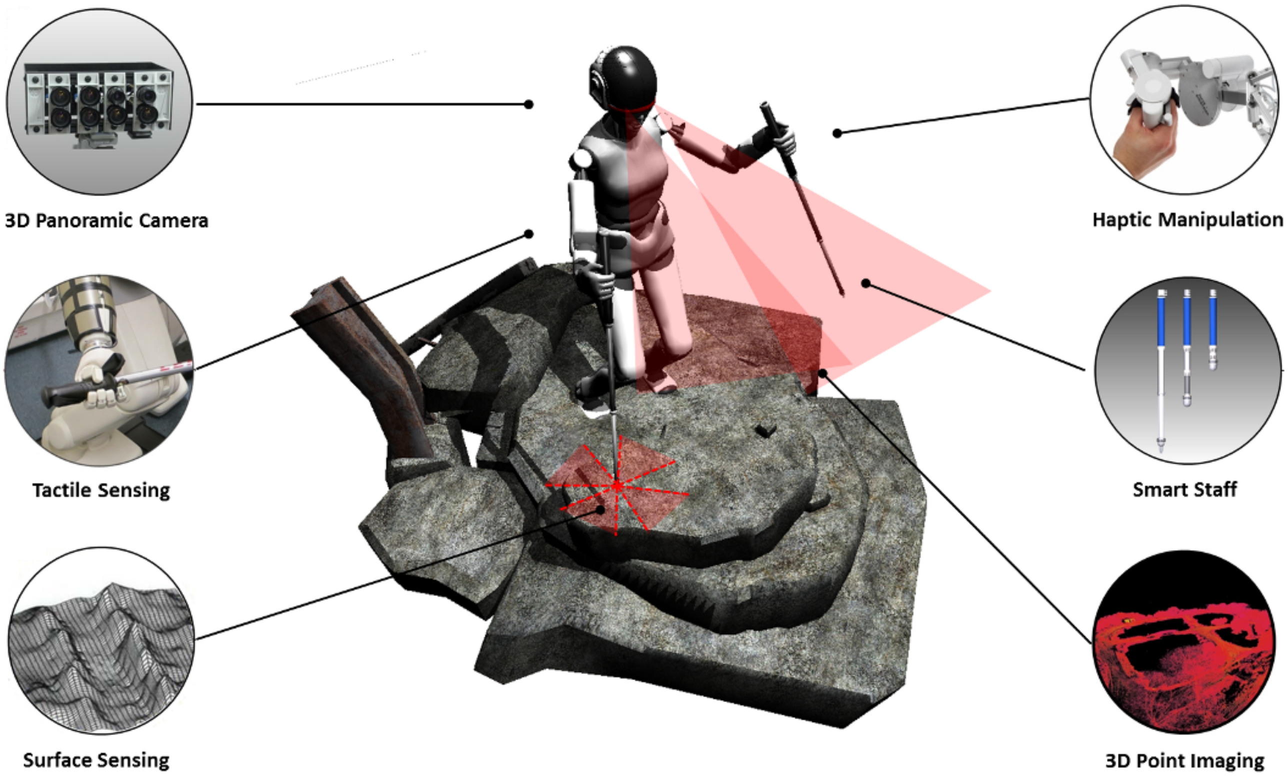

Fig. 2. SupraPed Framework: smart staff design with actuators and sensors, multi-contact whole-body control, locomotion and manipulation planning, 3D vision and tactile perception, and haptic tele-operation.

In addition, their extra limbs expand their support region [15] and improve stability while traversing uneven terrain. Bipeds, on the other hand, excel at navigating through narrow passages and at maximizing their available workspace while manipulating objects. Most unstructured environments, however, require a combination of both, which makes the SupraPed platform ideal for augmenting humanoid robots.

To synthesize complex behaviors of humanoid robots, a unified whole-body control framework [16], was presented to integrate manipulation, locomotion, and diverse dynamic constraints such as multi-contact interaction obstacle avoidance, and joint limits. This framework integrates task-oriented dynamic control and control prioritization, allowing robots to control multiple task primitives while complying with physical and movement-related constraints. This paper extends the whole-body control framework to address the control requirement for SupraPed locomotion in 3D unstructured environments, in particular, the unification of friction constraints into the multi-contact control architecture.

This paper is organized as follows: Section II gives an overview of the SupraPed framework and briefly describes the submodules and how they interact in the entire architecture. Section III presents a friction-consistent multi-contact control framework for SupraPeds. Section IV shows the simulation results of different scenarios in 3D unstructured environments. Finally, section V concludes the paper.

II. Overview of the SupraPed Platform

The SupraPed platform includes a pair smart walking staffs, a whole-body multi-contact control and planning software system, and real-time reactive controllers that integrate both tactile and visual information. Moreover, to bypass the difficulty of programming fully autonomous robot controllers, the SupraPed platform contains a remote haptic tele-operation system which allows the operator remotely give high level command. The overview framework of SuprePeds platform is sketched in Fig. 2.

SupraPeds platform is developed with a focus on the four topics consisting of: 1) Smart staffs that are equipped with actuators and multiple sensors. 2) A framework for humanoid multi-contact whole-body control and planning. 3) 3D vision and tactile perception for local control and feedback to the operator. 4) A remote console with graphical displays and bimanual haptic devices. The following sections will discuss more details about these four topics.

A. Sensing and Actuation for Walking Aids

The robot is equipped with two SupraPed staffs, which are normally carried clipped to the robots abdomen. When the robot requires extra sensing and mobility, it detaches one or both staffs from its body, attaching them to the wrist using a docking and locking mechanism. At this point, the staff becomes like a hikers pole, able to support loads and substantially enhance the robots stability margin. For legged locomotion, the support region [15][17] is one of the efficient ways to examine the feasibility moving the center of mass (CoM) while maintaining balance. When CoM is within the support region, it ensures that at least one set of contact forces is available to counterbalance the resultant forces and moments generated by the robot's weight. Table I and Fig. 3 show the increased area of support region in percentage (with respect to that of a standing biped) under different maximum supporting force constraints applied at the SupraPed staffs. Without loss of generality, the maximum supporting force is represented by percentage of total weight of the robot. As seen in Table I, with the constraint set at only 20% of body weight, the supporting forces on SupraPed staffs is able to double the area of support region.

In order to increase the versatility of the SupraPed staff with respect to a passive instrumented cane, the SupraPed staff is designed to be telescopic. This allows the robot to adjust the length of the staff in different situations. For instance, the shorter length is useful when the robot is bent over, kneeling, or righting itself from a fall. The longer length helps the robot extend the support region of CoM and further improve the stability of locomotion.

The SupraPed staff also acts as an exploration and extended sensing device. It allows the robot to make direct tactile assessments of surfaces before stepping on them. For probing surfaces, the SupraPed staff is equipped with tactile and visual sensing to perceive local information of the terrain immediately ahead of and to each side of the contact point. These information can provide feedback signals to the whole-body multi-contact control system and to the human operator, who uses this data as supportive information during exploration tasks and during locomotion and contact planning.

TABLE I

CoM FEASIBLE REGION VS MAXIMUM SUPPORT FORCE

Max. Support Force (%)	10	20	30	40	50	60
Area of Support Region(%)	151	209	265	316	361	400

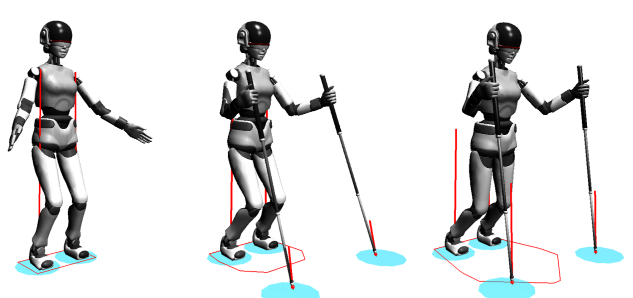

Fig. 3. The enlarged support region of CoM under different maximum supporting forces of SupraPed staffs. Red polygons show the estimated support regions of CoM. The maximum force constraint on staffs is represented in percentage of robot's weight. left: biped support. middle: SupraPed generates 209% support region of biped support under 20% maximum force constraint. right: SupraPed generates 400% support region of biped support under 60% maximum force constraint.

B. Multi-Contact Whole-Body Control and Planning

A guiding principle to overcome the complexity of building fully autonomous SupraPeds is to maximize robot autonomy using control and local planning, and to place a human operator at the highest possible level such that planning can be dramatically simplified. A critical functionality that our SupraPed platform must support is real-time interactivity, which allows the human operator to instantaneously intervene and handle critical events like preventing falling or helping an injured human. Enabling real-time interactivity, however, is complicated by the high dimensionality of the control problem (the numerous degrees-of-freedom) and dynamic environmental constraints. Solving such problems in real time is challenging, and we believe that the best strategy is to decompose potentially complex planning problems into simpler sub-problems, which we can solve with efficient canonical control primitives. The global planning problem can be simplified to selecting a sequence of sub-problems to solve, where a tele-operating human can quickly intervene if needed.

To take advantage of the enhanced stability from contact-supports and to realize multiple manipulation primitives, a real-time constraint-consistent multi-contact whole body control framework is required. This framework is an extension of previous work on synthesizing control vectors using a recursive priority-oriented operational space controller [16] [18] [19]. The details of the proposed control framework will be addressed in section III.

C. 3D and Multi-viewpoint Imaging

Considering a humanoid robot moving through a disaster site, strewn with obstacles and debris, visual sensing devices will be equipped at the head for navigating and planning motions, and also at the SupraPed staff tips for extended visual probing into areas out of view from the head and for positioning guidance when augmented support is required. These cameras are able to perceive 3D geometric information of surrounding environments. In the mean time, the acquired video from these visual systems provide the operator clear human-aspect and up-close perspectives of the task area, structured for binocular viewing and enhanced with depth information to aid his control.

D. Haptic and Visual Interface Design

To make effective use of biped robots equipped with the SupraPed, a sufficient level of autonomy is given to the robot, but it does not act solely on its own. A human operator will be in the loop, receiving 3D visual information along with his haptic feedback. In order to enable operators to perform dexterous manipulation motions with the robot arms while the robot body and perhaps parts of the arms are in contact with the environment, a bimanual haptic interface is introduced. With this, operators are able to physically feel external forces that are acting on the robot arms during manipulation tasks [20][21] and get intuitive haptic feedback during navigation [22].

III. Whole-Body Control framework for SupraPeds

Besides joint limits, torque and other motion constraints, locomotion through multiple contacts also need to deal with the problems of CoM shifting, weight distribution and friction constraints at the contacts. It involves the complex interdependencies between whole-body contacts and their relationship with CoM and task behaviors. So far, the control of handling multi-contact situations is not yet well understood. In order to perform complex locomotion behaviors, a new whole-body control framework is proposed to fuse the SupraPed staffs with any arbitrary robotic structure and to manipulate and maneuver humanoids efficiently in unstructured environments. The proposed control framework is capable of autonomously generating sufficient supporting forces from all contacts while complying with friction constraints by controlling the internal forces between contacts. By combining with prioritized control structure [23], we can further formulate a unified force-level control of supporting forces, internal forces, constraints, tasks and postures.

A. Friction-Consistent Whole-Body Control Framework

When the robot contacts environments with its extreme limbs, the dynamics equation of robot motion in joint space is expressed as

$$A(q)\ddot{q} + b(q,\dot{q}) + g(q) + J_{contact}^T f_{contact} = \Gamma \tag{1}$$

where A is the joint space inertia matrix, b is the Coriolis/centrifugal forces and g is the gravity compensation forces. q is the vector of joint angles and Γ is the vector of joint torque. The term, $f_{contact}$, is the vector of contact forces and moments. $J_{contact}$ is the corresponding Jacobian.

To handle multi-contact and under-actuation constraints of humanoid robots, a contact-consistent control framework was proposed in [24] to ensure that the tasks will not interfere the contact states of the robot by projecting the tasks to the null space of contacts $N_{contact}$ which is defined as the following.

$$N_{contact} \triangleq I - \bar{J}_{contact} J_{contact} \tag{2}$$

where $\bar{J}_{contact}$ is the dynamically-consistent inverse of $J_{contact}$. According to [24], Eq.(1) can be rewritten as

$$A(q)\ddot{q} + b_{contact} + g_{contact} = (U N_{contact})^T \Gamma_a \tag{3}$$

where

$$b_{contact} = b - J_{contact}^T \mu_{contact} \tag{4}$$

$$g_{contact} = g - J_{contact}^T p_{contact} \tag{5}$$

$\mu_{contact}$ and $p_{contact}$ are the projected Coriolis/centrifugal and gravity forces at the contact. U defined in Eq.(6) is the selection matrix of actuated quantities and Γ_a is the $n \times 1$ vector of actuation torques.

$$U = \left([0]_{n\times 6} \quad [I]_{n\times n}\right) \epsilon\, R^{n\times(n+6)} \tag{6}$$

While the contact-consistent control framework guarantees that all the tasks obey the contact constraints, it does not assure that the reaction forces on the contact links satisfy the friction constraints. In unstructured environments, robots usually have to engage the contacts on surfaces which normal vectors that are not in the direction of gravity. In such circumstance, the robot might easily slip and lose contacts. The contact forces, therefore, should not only provide sufficient supporting forces to maintain the balance but also need to satisfy the friction constraints to prevent slippage. Contact forces in robotic grasping problem are usually divided into the manipulation forces and the grasping forces. Manipulation forces contribute to the total resultant force and moments which are related to the motion of the grasped object. The grasping forces control the internal forces to maintain grasp stability and friction consistency.

Similar to the grasping problem, the contact forces and moments $f_{contact}$ in this paper are composed of f_r and f_t.

$$f_{contact} = f_r + f_t \tag{7}$$

f_r provides sufficient supporting forces and moments, f_s, to counterbalance the resultant forces and moments generated by the weight and motion of the robot. On the other hand, f_t contributes to the internal forces and moments, f_{int}, which belongs to the null space of the supporting forces and moments, N_s. Using the grasp matrix W and virtual linkage model E [25], we can map the contact forces and moments to the supporting and internal forces and moments as Eq.(8).

$$\begin{bmatrix} f_s \\ f_{int} \end{bmatrix} = \begin{bmatrix} W \\ \bar{E} \end{bmatrix} f_{contact} = \begin{bmatrix} W & 0 \\ 0 & \bar{E} \end{bmatrix} \begin{bmatrix} f_r \\ f_t \end{bmatrix} \tag{8}$$

where $\bar{E}$ is the left inverse of virtual linkage model E. From Eq.(8), $f_{contact}$ can be represented by f_s and f_{int}.

$$f_{contact} = \bar{W} f_s + E f_{int} \tag{9}$$

where $\bar{W}$ is the pseudoinverse of W. The external torques, $\Gamma_{contact}$, generated by $f_{contact}$ is then expressed as

$$\Gamma_{contact} = J_{contact}^T f_{contact} = J_s^T f_s + J_{int}^T f_{int} \tag{10}$$

where

$$J_s = \bar{W}^T J_{contact} \tag{11}$$

$$J_{int} = E^T J_{contact} \tag{12}$$

J_s and J_{int} are the corresponding Jacobians of f_s and f_{int}. Substituting Eq.(10) to Eq.(1), the dynamics of robot motion can be reformulated as

$$A\ddot{q} + b + g + J_s^T f_s + J_{int}^T f_{int} = \Gamma \tag{13}$$

With the assumption that the contact points are rigid-body contacts and the velocity and acceleration of contacts being equal to zero, the resultant velocity $\dot{x}_s$ and acceleration $\ddot{x}_s$ which can be derived from Eq.(11) using the jacobian. By multiplying Eq.(13) by $J_s A^{-1}$ and considering the equality $\ddot{x}_s = J_s\ddot{q} + \dot{J}_s\dot{q}$, the required supporting forces and moments, f_s, to maintain the balance can be computed by

$$f_s = \bar{J}_s^T \Gamma - \bar{J}_s^T \left(J_{int}^T f_{int}\right) - \mu_s - p_s \tag{14}$$

According to Eq.(13) and (14), the constrained dynamics equation in Eq.(3) can be rewritten as

$$A\ddot{q} + b_s + g_s + N_s^T \left(J_{int}^T f_{int}\right) = \left(UN_s\right)^T \Gamma_a \qquad (15)$$

By combining the prioritized multi-task control framework in [23], the SupraPeds torque-control representation for humanoid robot is characterized as

$$\begin{aligned}\Gamma =& J_{int|s}^T F_{int} + J_{c|int|s}^T F_c + J_{t|c|int|s}^T F_{tasks} \\ &+ J_{p|t|c|int|s}^T F_p\end{aligned} \qquad (16)$$

where the symbols c, t, and p denote constraints, tasks and postures respectively. The subscript following by | indicates prioritization. For instance, subscript $int|s$ denotes that internal forces and moments are consistent with supporting forces and moments. As can be seen from Eq.(16), all the controlled forces and moments are consistent with supporting forces and moments without interfering the balance of the robot. By correctly controlling the internal forces and moments, we can ensure the consistency of friction constraints.

B. Internal Force and Moment Control

The goal of controlling the internal forces between contacts is to ensure the feasibility of contact forces. Instead of using complex optimization methods such as linear [26][27] or non-linear programming [28][29] to calculate the optimal internal forces, this paper formulated the force constraints as weighted barrier functions and gradually approaches the optimal internal forces F_{int}^* by Newton's method as proposed in [30].

$$F_{int,k+1}^* = F_{int,k} + \Delta F_{int,k} \qquad (17)$$

$F_{int,k}$ indicates the internal forces in time step k. Moreover, the iteration process of Newton's method can be easily integrated into a torque-based internal force controller given by

$$\Gamma_{int,k} = J_{int,k}^T \left(\Delta F_{int,k} + p_{int,k}\right) \qquad (18)$$

where p_{int} is the gravity force projected on the internal force space.

IV. Simulation Results

The performance of proposed control framework has been validated and analyzed through dynamics simulations. The simulator, SAI, which includes dynamics, graphics and control modules has been developed in our lab for several years. All the simulations run on the robot model, HRP4C [4]. In order to easily observe the feasibility of the contact forces, all the contact forces in simulations are represented by the ratio μ_i of corresponding forces in tangent and normal directions of contact surfaces. To be within the friction cone thus preventing slippage this ratio must be less than the friction coefficient μ_0. Here we used $\mu_0 = 0.8$ in all the simulations. The simulation video can be found at [31].

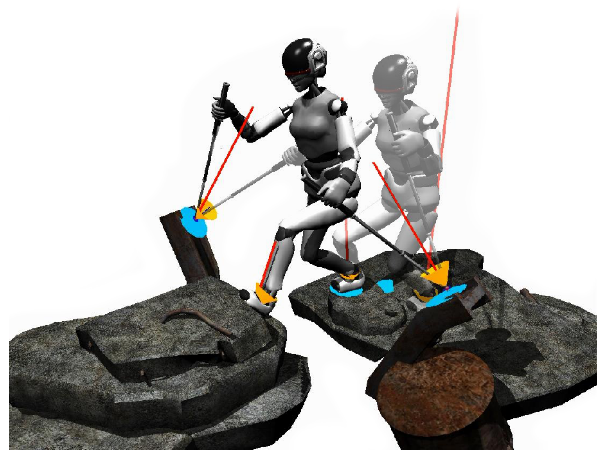

Fig. 4. Simulation I: the robot makes three contacts with the environment while swing its left foot. The proposed control framework automatically generates appropriate contact forces to support the robot's weight and comply with friction constraints.

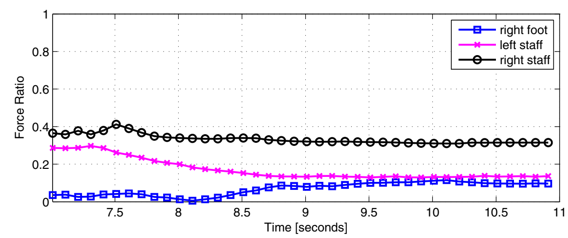

Fig. 5. Simulation I: With internal force control, the forces on all contact links complied with the friction constraint ($\mu_i < \mu_0,\ \mu_0 = 0.8$)

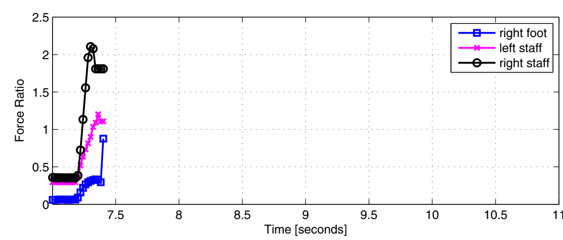

Fig. 6. Simulation I : Without internal force control. Because of the slippage on right staff, the simulation was terminated at 7.3 seconds

A. Simulation I

In the first simulation, the robot is swinging its left foot while three links, right foot, right staff and left staff, are contacting with the environment as shown in Fig. 4. Fig.5 and Fig.6 display the force ratio of contacts with and without the internal force control during the swinging phase. As can be seen, controlling the internal forces ensures that the force ratios are always below the friction coefficient μ_0. On the contrary, in Fig.6, because of the rapidly increased force ratio in right staff, a slippage happened at 7.3 seconds when the robot is under no internal force control. This simulation demonstrates that the proposed control framework is able to autonomously generate the supporting forces and further comply with the friction constraint by controlling the internal forces.

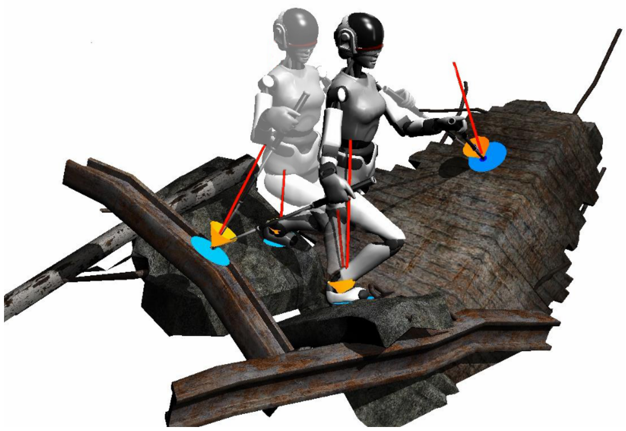

Fig. 7. Simulation II. The robot makes four contacts with the environment. The CoM is controlled to perform sine wave motion in forward/backward direction. To maintain the stability of the contacts, the internal forces between the contact links are controlled by the proposed method in section III.

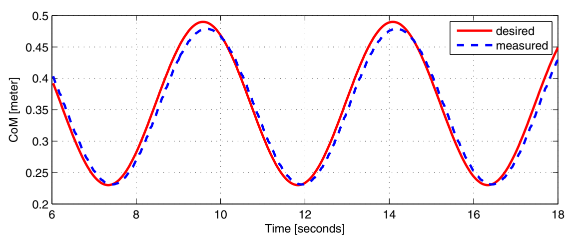

Fig. 8. Simulation II : CoM trajectory

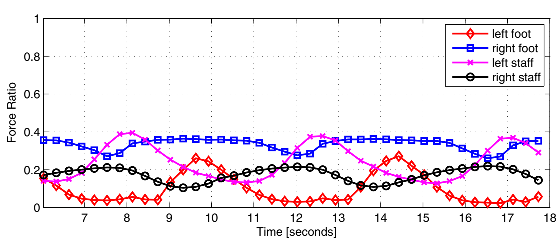

Fig. 9. Simulation II : Controlling the internal forces effectively stabilizes the contacts by reducing the force ratios, μ_i, on all contact links.

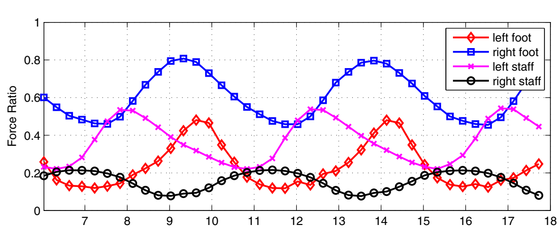

Fig. 10. Simulation II: Without internal force control, the force ratios, μ_i, on all contact links are higher than those under internal force control. A small disturbance could easily make the robot lose the contacts.

B. Simulation II

The second simulation demonstrates that the robot performs the sinusoidal position tracking control of CoM while contacting with the environment with both feet and staffs. CoM is controlled to follow a sine wave motion in forward/backward direction which changes the total resultant forces and moments of the robot at different time steps. To maintain the balance, the contact forces must comply with this sine wave motion. Fig. 8 displays the control result and further verifies that the proposed control framework is able to provide sufficient supporting forces and moments to counterbalance the various resultant forces and moments generated by the robot's weight and motion. Moreover, Fig. 9 and Fig. 10 display the corresponding force ratio of contacts with and without internal force control. It shows that internal force control efficiently reduces the force ratio and increase the stability of the contacts while robot executes the motion task. This simulation demonstrates that the proposed control framework enables the decoupled control on CoM motion, supporting and internal forces.

C. Simulation III

The final simulation demonstrates that SupraPeds provide excellent ability of locomotion in a 3D unstructured environment by switching among bipeds, tripeds and quadrupeds. One of the critical factors to maintain the stability of locomotion is to smoothly change the contact forces during the periods of engaging and disengaging contacts. Before lifting off a contact, its contact force needs to be gradually decreased and distributed to other contacts. On the other hand, the contact force is smoothly increased when the robot is engaging a new contact. To solve this problem, we embedded a control primitive to automatically adjust the weights of the inverse grasp matrix, $\bar{W}$, to generate smooth contact forces. Fig. 11 shows the simulation result.

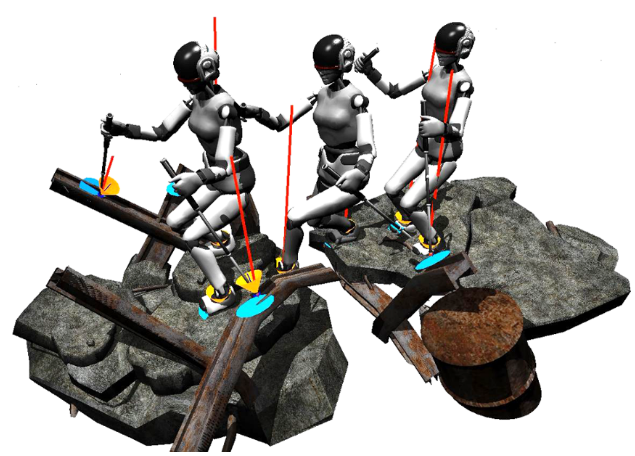

Fig. 11. Simulation III. The robot traverses the rough terrain by switching among biped, tripeds and quadrpeds. The simulation video is demonstrated at [31].

V. CONCLUSIONS

In this paper, we proposed the concept of SupraPed platform, a set of smart staffs, a suite of multi-contact control model, and a haptic tele-operation system, that transforms biped humanoid robots into SupraPeds tripeds or quadrupeds. Moreover, a friction-consistent whole body control framework is proposed to addresses the requirements of SupraPed locomotion in 3D environments. Dealing with multiple contacts, the grasp matrix and the virtual linkage model are integrated to the dynamics model and are applied to re-organize contact forces into supporting and internal forces. With decoupled structure of supporting and internal forces, it allows robots to perform autonomous balancing while complying with friction constraints by controlling the internal forces. Simulation results have demonstrated that the integration of the SupraPed platform and the proposed control framework significantly enhance the locomotion performance of humanoid robots in unstructured rough-terrain environments.

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