Design a Fall Recovery Strategy for a Wheel-Legged Quadruped Robot Using Stability Feature Space

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Design a Fall Recovery Strategy for a Wheel-Legged Quadruped Robot Using Stability Feature Space

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Abstract— **In this paper, we introduced a conceptual analysis to select stability features when performing predefined and precise motions on robots. By analyzing the different stable poses named features and the possible transitions towards different ones, the introduced concept allows to design more predictable and suitable motions when performing particular tasks. As an example of how the concept can be applied we use it on the fall recovery of the quadruped robot CENTAURO. This robot, which is equipped with a custom hybrid wheel-legged mobility system, have good intrinsic stability as other quadrupeds. However, the characteristics of the rough terrains where it might be deployed require complex maneuvers to cope with possible strong disturbances. To prevent and more importantly recover from falls, realignment of postural responses will not be adequate, and effective recovery procedures should be developed. This paper introduces the details of how the presented conceptual analysis provides and an effective fall recovery routine for CENTAURO based on a state machine. The performance of the proposed approach is evaluated with extensive simulation trials using the dynamic model of the CENTAURO robot showing good effectiveness in recovering the robot after fall on flat and inclined surfaces.**

I. INTRODUCTION

Nowadays, In field robotics, technologies are being provide with further autonomous capabilities to minimize the pilots interaction while performing different actions including, but not limit to, manipulation, locomotion, mapping, etc.

However, in many application, the precise intervention of the pilots and a step by step task design is required. A particular example might be the case of fall recovery task in quadruped wheel-legged robots. These robots has been attracting interest, as they combine the advantages of wheels and articulated legs [1], [2]. In addition, compared to bipedal robots, the quadruped configuration provides enhanced intrinsic balance capabilities given the larger support polygon and the ability to modulate it through the richer combinations of motions [3], [4]. This makes quadruped robots an interesting technology to be used in complex environments where the terrains are difficult to traverse. e.g., rescue scenarios, wild terrains, and exploration scenarios.

To properly deploy robots in these environments, self recovery capabilities must be included [5], [6]. These methods will permit the robot to recover from a fall or a shut-down, avoiding the operator's intervention after certain unexpected failures in motion execution. Even though falls are expected to be less frequent in quadruped platforms, terrains where quadrupeds are introduced, are complex and may still force falling incidents [7], [8]. Therefore, recovery routines for quadruped robots are also required.

In this paper, we present a recovery strategy for a quadruped robot. The platform used to validate it is the wheeled-legged quadruped CENTAURO [9], The robot's design provides physical robustness against disturbances, rich proprioception including joint torque sensing, and other advantageous characteristics such as its hybrid wheeled-legged mobility features.

The proposed method relies on a state machine and controls the robot at the joint level. To select the state machine nodes that describe the recovery strategy, we consider all possible static robot-terrain interactions as stable states of the robot. These states are named as features. Additionally, we describe the different transitions between features that can exist when the robot modifies its position. In this way, a more refined criteria for the state machine nodes selection emerge. The developed criteria is applied to select the proper recovery sequence for the CENTAURO robot.

Given CENTAURO's characteristics, this method allows the quadruped to recover and stand up not only over flat terrains, but also on inclined ones, as it will be shown throughout the paper. However, it can also be used to find in an intuitive manner reliable state transitions for different robots. To avoid issues such as singularities, joint limits, or non-convergence during the inverse kinematics (IK) solution, we decided to implement simple joint level control IK with predefined trajectories according to each states.

II. STATE OF THE ART

In several applications, it is necessary to design scenarios that allow robots to follows a precise sequence of motions towards a desired gait. Some examples of these might include: shutdowns, falls and precise stepping. However, if we consider the quadruped robots fall recovery state of the art, not many of them are able to stand from a falling configurations, limiting their effectiveness in real applications. This issue has been considered in different types of platforms including bipeds [5], [10], [11] and other robots [12], [13].

In [14], the authors made use of whole-body optimization procedures developed for the execution of non-periodic tasks on quadrupeds. To this aim, the authors defined the cost function according to the desired goal allowing the robot to reach the final position from different scenarios and postures.

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As a particular example of this work, the authors showed the capability of the robot to recover from a failed locomotion task. In this work, each scenario required a different cost function and generalization is difficult to be addressed.

Another approach was presented in [15], where predefined poses were designed that allow the humanoid robot HRP-2P to recover from supine or prone positions to an upright posture. These poses provide a cycle of stable configurations that the robot is able to execute and where it will have static balance. However, this work did not provide a methodology to select the stable motion during the fall recovery.

Other stand-up routines used learning techniques as in [5], [10]. The use of learning methods is attractive since it permits to extend these methodologies to other robots which have similar characteristics with minimal modifications. However, these techniques are time-intensive and in different cases, require heuristic knowledge for the pose combinations to be executed, as in [10]. In this work, the authors used human body behavior recordings to train the system. The training data was chosen carefully to agree with their hardware characteristics. Therefore, previous knowledge and good computational power were required.

As can be seen from the state of the art, the stand-up motion can be described as a challenge that is hardware-dependent, which makes difficult the development of a general strategy that can apply to different hardware. This also applies for quadruped robots and in particular for the CENTAURO robot considering its dynamics and body physics. As in the literature, where most of the methods are hardware-dependent, and the method presented in this paper is not an exception.

The proposed methodology aim's to provide an analytic point of view in designing the predefined poses such that the motions are less expert dependent and easily generalized based on transition and poses analysis. In the case of CENTAURO, the analysis allows us to define a set of poses and transitions such that the robot stands up not only over flat terrain but also on inclined terrain. To produce a successful motion, it is desirable that the transition between static poses is smooth. In this way, the hardware and its surroundings are protected, which is of particular importance in field robotics to avoid further damage.

III. Stability Feature Spaces

The contact states of a robot can be represented using a set of multidimensional feature spaces. For the sake of simplicity, here we show only the 2D conceptual projection of all the feature spaces as depicted in Fig. 1. The colored spaces show the robot's different contact states with the environment, where their sizes are constrained by the robot's design and motion states, such as robot posture, torque limits, robot dimensions, Center of mass (CoM) acceleration, etc.

The spaces surrounded by a solid line represent a stable multi-contact state, where the robot keeps its static stability as long as the same contact condition is remained. Outside of the stable space, the area surrounded in dashed lines represents a falling state of the same contact condition, where if no additional efforts were made, the robot will inevitably reach another stable space (commonly to a fell down contact condition). However, if taking correct recovery actions, the robot will recover its balance back to the stable space, such as arm strategy for bipedal standing balancing, or to a new desired stable space, such as dynamic walking.

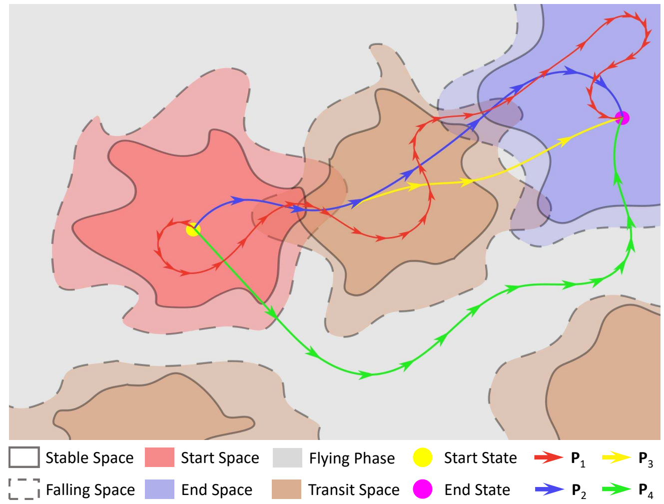

Fig. 1. Conceptual diagram showing the multi-dimensional stability features of the robot.

In line with this explanation, we can define n feature spaces that represent different contact states for a robot. Taking as an example the case of the robot CENTAURO performing a recover gait, and based on the robot characteristics, we can define three relevant feature states, note that different recovery paths and features can be define though. The first represents the robot lying down on one side. In the second state, called transition space, the robot remains on the floor with the four legs on the ground, and the CoM is in a low position. The final state represents the robot with all four legs in contact with the ground and maintaining the final desired posture.

In addition, as depicted in the Fig. 1, a feature space has several intersection that represents the existing relations with other spaces, which are listed as follows:

- *Stable-Stable*: Having two features A and B, the Stable-Stable relation is given when the intersection of both features happens between the stable areas each one, i.e, static walking gait where the contacts are changing constantly between double support and single support [16], [17].
- *Unstable-Stable*: Intersection of feature A's stable area and feature B's non stable area, i.e, a reactive step to avoid a fall in a robot. [18], [19].
- *Unstable-Unstable*: Intersection of unstable areas of features A and B, i.e, during a locomotion gait in slippery terrain [20]. In this scenario, additional balance and recovery actions need to be considered to avoid flying phases and complete the locomotion.
- *NoIntersect*: Two feature spaces are not intersected and separated by a flying phase, i.e, running gait for

humanoids [21] or quadrupeds [22].

These feature states can be used, for instance, if we want the robot to change from a start state (e.g. a supine pose) to an end state (e.g. a standing pose). In this example, no direct static transition exists (a NoIntersect relation), and we could pass through a transition space (e.g. a sitting pose) to stabilize the motion. As shown in Fig. 1, a number of motion paths with different characteristics exist that can produce a transition from a start space to a target end space.

The path $\mathbf{P_1}$, which is shown in red, represents a non-optimal trajectory that, however, permits to navigate from the start space to the transition space with a Stable-Stable relation. Therefore the stability of the transition is guaranteed. Once the transition space is reached, the trajectory drives the motion to the end space passing through an Unstable-Stable intersection to finally reach the end state. In this Unstable-Stable transition, stability depends on the controllers or the space definition and the motions dynamics, i.e, a controlled fall to the desired direction.

A similar path is represented by $\mathbf{P_2}$ (blue path in Fig. 1), which represents an optimal solution to travel from the above-referenced start state to the end state. In this case, the transitions are the same ones presented in $\mathbf{P_1}$. However, the optimal solution provides a softer, faster, and more accurate path from the start space to the end space.

A different path is given by $\mathbf{P_3}$ (yellow path in Fig. 1). In this case, the path consists of the same first interaction (Stable-Stable intersection), as in the previous cases. However, to pass from the transition space to the end space, the path needs to pass through a flying phase, the NoIntersect relation. In this case, the stability of the transition is not guaranteed and the success of the motion will depend on the trajectory definition and stable space characteristics, e.g, an intended jump motion.

Finally, $\mathbf{P_4}$ (green path in Fig. 1) represents a flying trajectory from the start state to the target end state. In this case, the motion starts from a stable feature in the start space. To drive the motion to the end space, the trajectory directs the robot towards the flying phase area to reach the end space directly. As an example of this kind of transition, we can think of a jump forward on two feet instead of performing one step in a bipedal walk.

From the implementation point of view, in general, it is desirable to traverse between features with Stable-Stable intersections. This will provide static stable transitions and assure the safety of the robot. Therefore, $\mathbf{P_1}$ and $\mathbf{P_2}$ provide the desired motion behavior in the space representation.

$\mathbf{P_1}$ can be found based on previously known sub-optimal behaviors of the robot, while $\mathbf{P_2}$ requires optimization methods and complex algorithms which is not part of this paper.

IV. CENTAURO Rising Example

In this work, we used a state machine to allow the robot to recover the standing posture following a fall. Given that the defined states represent stable poses of the robot that were found heuristically, our approach designed a motion path similar to $\mathbf{P_1}$ in Fig. 1. Therefore, a set of transitions between different stable poses of the robot are given without compromising the stability of the motion. This will allow the quadruped robot CENTAURO to recover from a fall in a secure way. To this aim, we define a state machine based on the presented concept identifying the different stable spaces according to the robot dynamic characteristics and analyzing the closer transition spaces between them.

This robot is a centaur-like robot that has a humanoid upper-body whit two 7 degrees of freedom (DOF) arms mounted on a torso with 1 DOF and a 2 DOF head. This humanoid upper body, is mounted on a wheeled quadrupedal lower-body. Each of the quadruped legs has 6 DOF legs with a wheel at the end-effector [23].

Additionally, the robot has a wide range of motion. For the arms it was considered the human ergonomic which was extended where possible. The range of motion of the legs was set such that the robot can operate and adapt to the different leg configurations for quadruped robots inward and outward knee arrangements. This will extend the robots capabilities and also the implementation of recovery actions [1]. For a complete hardware description refer to [9].

A. Rising Phases

The proposed state machine was designed following the concept in Sec. III for the quadruped robot CENTAURO. A similar procedure can be extrapolated for other quadrupeds with the corresponding hardware consideration. As shown in Fig. 2, we selected four contact conditions as the feature spaces to be performed by CENTAURO during the fall recovery motion. It can be seen in the proposed sequence from the initial state, feature 1, to the feature 2, there is a dynamic transition while in the other cases, the motions are statically stable. In feature 2, the CENTAURO has two legs and two feet contact with the environment; in feature 3, the contacts are the four feet (wheels) plus the pelvis of the robot. Finally, the end state, feature 4, has only four feet in contact with the ground. Notice that the space labels 4 and 4' have the same contact conditions, therefore they are both refer to the same feature space. However, their shapes are different due to the different configurations of the robot. We present them separately to clarify that even though the feature shapes and the robot configurations may be different, the feature space depends only on the contacts with the environment.

Given that the standing up routine should coexist with other control algorithms, the first focus must be fall detection. For this purpose, we read the IMU signals and define a threshold that identifies when the robot is falling. Once a fall is detected, the state machine takes control of the robot, and a new IK solver in the joint space is initialized.

The first state of the state machine aims to provide a secure fall. This marks the first transition for an unknown non-stable robot state to a known stable state (lying down in the floor). The transition between these two features depends on the motion and final robot falling position, but cannot be predefined. Considering that in the CENTAURO case the head of the robot houses delicate hardware (cameras and a laser), the arms of the robot are used such that the contact

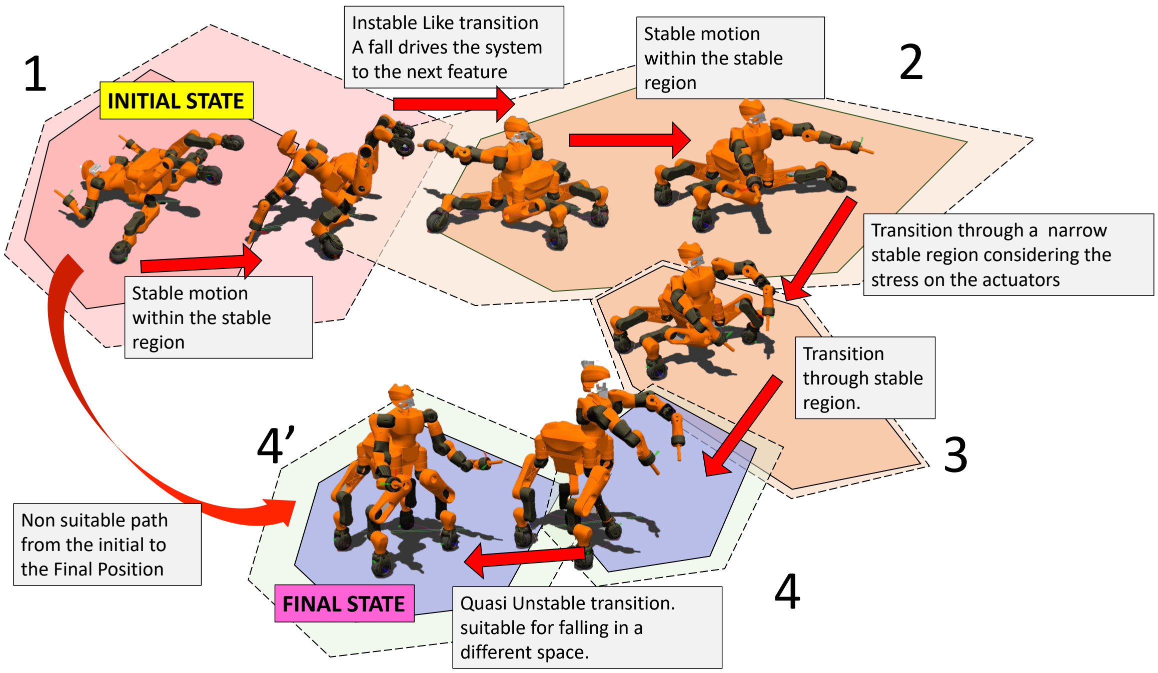

Fig. 2. Selected features for the stand up motion on CENTAURO robot.

of the head with the floor is minimized and the arms work as an armor for the sensors and hardware.

During the fall, the legs are moved such that the CoM is closer to the ground. This leads to the desired falling position such that the robot adopts a lateral fall position. The legs that are in contact with the floor are extended in the sagittal plane, while the other two are extended in the y axis of the robot.

After the falling posture has been reached, the standing up routine makes the body rotate and place the trunk of CENTAURO parallel to the ground. To reach this state, we leverage on two behaviors. The first one is to raise the CoM as high as possible and push it out from the support polygon. In this way, we destabilize the previously stable feature to enable a transition towards a different feature. To that end, we extend the legs that are not in contact with the ground and extend the arms of the robot.

Secondly, by spreading the legs we create a vertex such that the body of CENTAURO can rotate easily. In this way, the transition from the falling state to the trunk rotation state is done softly even though the transition implies a dynamic fall of the body during the rotation.

The rotation propulsion is given by the arms. As depicted in Fig. 3 in the first snapshot, the elbows are flexed. Therefore, extending them will push the body up and generate the rotation of the trunk. The motion can be seen in Fig. 3. The arms push the body while the legs that are in contact with the terrain create the axis of rotation for the body. In addition, the other legs help to reduce the necessary force applied by the arms to generate the rotation.

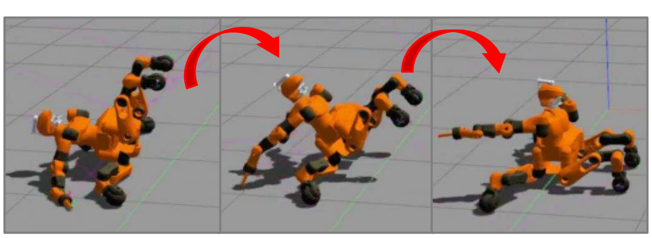

Fig. 3. Turning the body upwards

Once the robot's body is turned, the right legs are moved such that the support polygon is increased and the CoM is placed close to the ground. This provides a stable support region from which the robot will stand up in a secure way. In addition, the recovery will be possible also on sloped terrain as will be shown. Once the robot is placed on a horizontal position. The torso recovers the original heading and the robot rises providing stable trajectories for this aim.

V. State Machine

The implemented state machine is reported in Fig. 4. As can be seen, the first state is the waiting state. If the IMU readings are under the defined threshold, there is no fall detection and the robot continues working on other tasks. If a fall is detected, the system is initialized for fall recovery. To this end, the first stage is to change from a general purpose IK solver to the joint space one used for the fall recovery.

Afterwards, the body of the robot moves towards the lateral falling position (identified as "Falling posture" in Fig. 4). During the fall recovery, if a new fall is detected, the procedure starts from this state. Once the falls occurs, a new feature is called. This step will rotate the body to recover the horizontal orientation of the body.

The maximum number of trials is set to three. Afterwards, a new start from the falling posture takes place. Once the turn up of the body happens (Recover Torso Heading), the

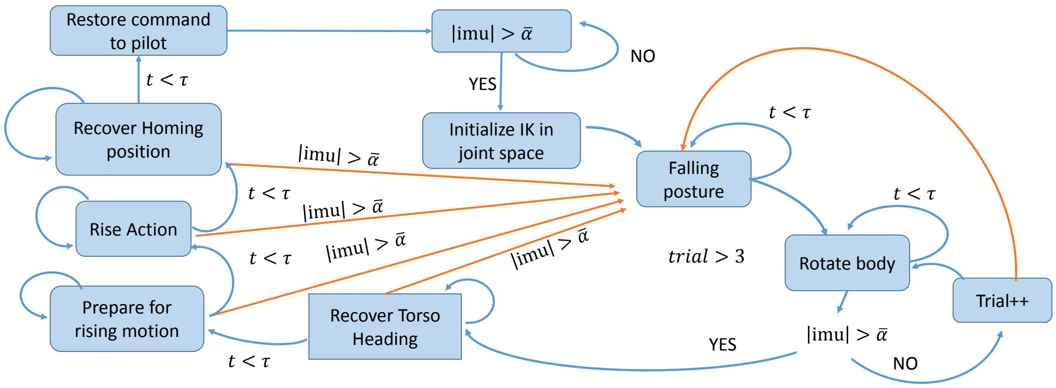

Fig. 4. Implemented state machine for the CENTAURO fall recovery

trunk heading and arms are recovered, taking advantage of the large support polygon the robot has at this point. In this way, we minimize the effect that such motion has over the CoM. Next, the robot should be prepared for the rising motion. In this state, the robot legs are positioned in a way that the four wheels are in contact with the ground plane. The rising action, extends the legs and recovers the CoM height. Finally, the initial configuration of the robot is recovered and the control passes again to the administrator.

A. *Simulation results*

To test the proposed stand up heuristic method for the CENTAURO robot, we implemented it in simulation using a model of the robot that has physical characteristics and constraints that are equivalent to those of the real one. We provide simulation results of the CENTAURO rising on flat and sloped terrain. Knowing the desired stable features, we define soft trajectories in the joint space that drives the robot smoothly towards the desired position.

Snapshots of the rising motion of the CENTAURO robot on flat terrain are depicted in Fig. 5. As can be seen, the robot is able to perform the desired motion passing through the different features previously defined. The transition from the initial fall posture to that in which the torso is upright (snapshot 6) happens dynamically as previously explained.

The effort done by the robot at each joint during the recovery gait is shown in Fig. 7. To make the transitions between features more visible, we extend the time that the robot remains on each feature. During the final state-machine execution these transitions are consecutive. As can be seen, the most demanding state happens during the steady state of the feature 4 after 60 seconds. Actually, due to the robot configuration, this state requires around 200 N for the knee joints (see Fig. 2 feature 4). Given these results, we can assume that the proposed method can be applied in the CENTAURO robot.

Given the characteristics of the selected features, we can use the same state machine to perform a rising motion on sloped terrain. As it is seen in Fig. 6, the CENTAURO can also performs the rising motion on a 20° inclined terrain. Given the large support polygon that is generated during the stand up phase, the motion is stable and allows a soft navigation through the predefined features. In the case we are presenting in this simulation, the positive elevation of the terrain allows an easier rotational motion in the first phase of the proposed strategy. However, similar performance is reached in negative slopes, though bigger effort by the arms is required.

VI. Conclusions

This work presents a fall recovery strategy for the CENTAURO quadruped robot. The proposed method relies on the definition of known feature spaces that provide safe and stable transitions for the robot during the recovery motion. To go through each stable feature space, close relations between feature spaces can be found to allow a secure and feasible recovery path transition.

The presented method was tested in simulation using the CENTAURO robot dynamic model. It was shown that the selected stable feature spaces allow the robot to recover from a fall in flat and inclined terrains. This capability will permit the robot to recover from a fall across a wider range of environments.

Future developments will consider to test the method on the real hardware with safe experimental conditions. Afterwards, it is desired to provide optimal trajectories through feature configurations and transitions to supply more reliable performance during the fall recovery motion.

References

[1] J. A. Castano, E. Mingo, A. Laurenzi, L. Muratore, M. gorzata Kamedula, and N. G. Tsagarakis, "A whole body attitude stabilizer for hybrid wheeled-legged quadruped robots," in *2018 IEEE International Conference on Robotics and Automation*, May 2018.

[2] G. Besseron, C. Grand, F. B. Amar, F. Plumet, and P. Bidaud, *Locomotion Modes of an Hybrid Wheel-Legged Robot*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2005, pp. 825–833.

[3] K. Turker, I. Sharf, and M. Trentini, "Step negotiation with wheel traction: a strategy for a wheel-legged robot," in *2012 IEEE International Conference on Robotics and Automation*, May 2012, pp. 1168–1174.

[4] X. Wu, X. Shao, and W. Wang, "Stable quadruped walking with the adjustment of the center of gravity," in *IEEE International Conference on Mechatronics and Automation*, 2013, pp. 1123–1128.

[5] H. Jeong and D. D. Lee, "Efficient learning of stand-up motion for humanoid robots with bilateral symmetry," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct 2016, pp. 1544–1549.

[6] J. Stückler, J. Schwenk, and S. Behnke, "Getting back on two feet: Reliable standing-up routines for a humanoid robot," in *IAS*, 2006.

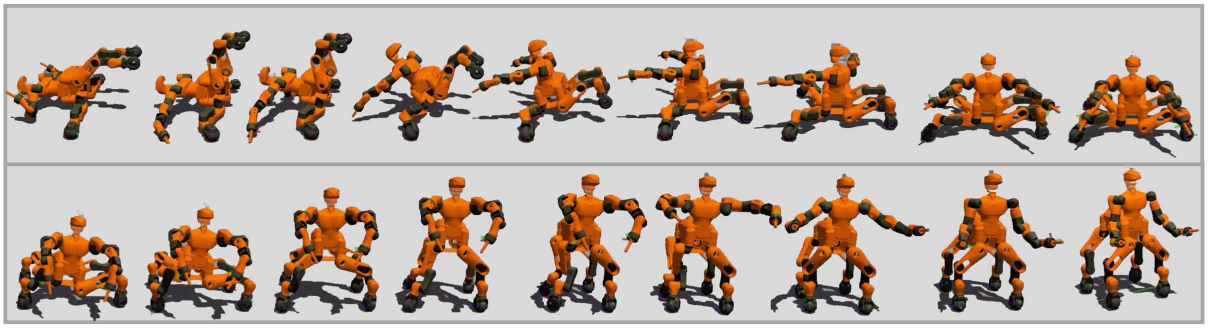

Fig. 5. Snapshots of the CENTAURO robot executing the rising motion on flat terrain

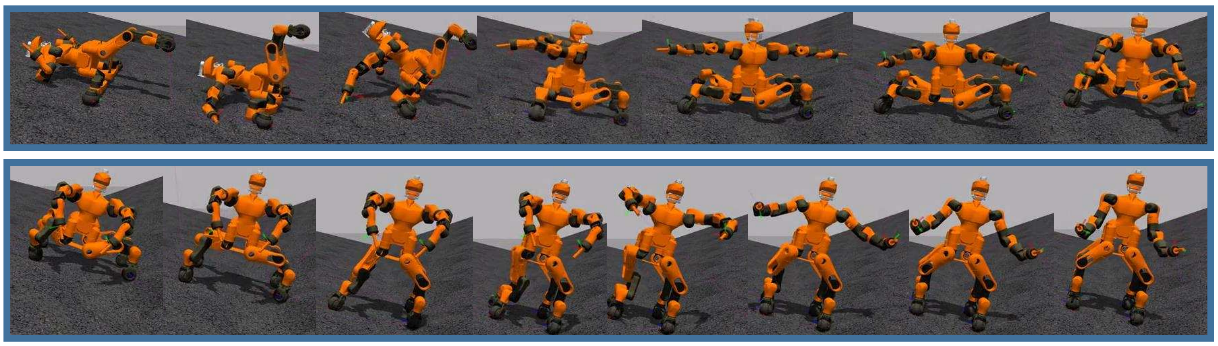

Fig. 6. Snapshots of the CENTAURO robot executing the rising motion on inclined terrain

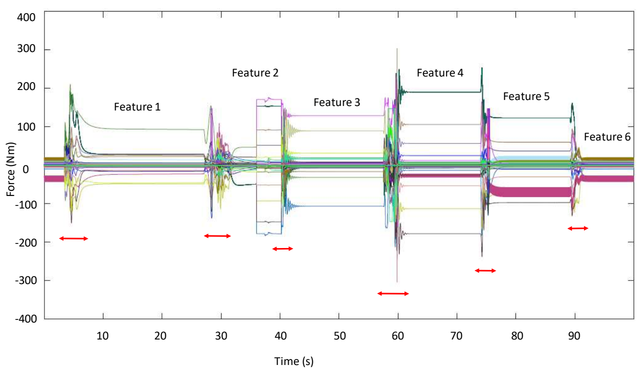

Fig. 7. Joint efforts during the CENTAURO recovery on flat terrain.

[7] G. Besseron, C. Grand, F. B. Amar, and P. Bidaud, "Decoupled control of the high mobility robot hylos based on a dynamic stability margin," in *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Sept 2008, pp. 2435–2440.

[8] K. Iagnemma, A. Rzepniewski, S. Dubowsky, and P. Schenker, "Control of robotic vehicles with actively articulated suspensions in rough terrain," *Autonomous Robots*, vol. 14, no. 1, pp. 5–16, 2003.

[9] N. Kashiri, L. Baccelliere, L. Muratore, A. Laurenzi, Z. Ren *et al.*, "Centauro: A hybrid locomotion and high power resilient manipulation platform," *IEEE Robotics and Automation Letters*, vol. 4, no. 2, pp. 1595–1602, April 2019.

[10] D. Luo, Y. Ding, Z. Cao, and X. Wu, "A multi-stage approach for efficiently learning humanoid robot stand-up behavior," in *IEEE International Conference on Mechatronics and Automation*, Aug 2014, pp. 884–889.

[11] M. Inaba, F. Kanehiro, S. Kagami, and H. Inoue, "Two-armed bipedal robot that can walk, roll over and stand up," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Aug 1995, pp. 297–302.

[12] J.-S. Yang and Y.-S. Chang, "Standing control of a four-link robot," in *2005 IEEE International Conference on Systems, Man and Cybernetics*, vol. 1, Oct 2005, pp. 679–684 Vol. 1.

[13] J. Morimoto and K. Doya, "Acquisition of stand-up behavior by a real robot using hierarchical reinforcement learning," *Robotics and Autonomous Systems*, vol. 36, no. 1, pp. 37 – 51, 2001.

[14] A. Radulescu, I. Havoutis, D. G. Caldwell, and C. Semini, "Whole-body trajectory optimization for non-periodic dynamic motions on quadrupedal systems," in *2017 IEEE International Conference on Robotics and Automation (ICRA)*, May 2017, pp. 5302–5307.

[15] F. Kanehiro, K. Kaneko, K. Fujiwara, K. Harada, S. Kajita *et al.*, "The first humanoid robot that has the same size as a human and that can lie down and get up," in *IEEE International Conference on Robotics and Automation*, vol. 2, Sept 2003, pp. 1633–1639.

[16] C. Zhou, X. Wang, Z. Li, and N. Tsagarakis, "Overview of Gait Synthesis for the Humanoid COMAN," *Journal of Bionic Engineering*, vol. 14, no. 1, pp. 15–25, 2017.

[17] C. Gehring, S. Coros, M. Hutter, M. Bloesch, M. A. Hoepflinger, and R. Siegwart, "Control of dynamic gaits for a quadrupedal robot," in *2013 IEEE International Conference on Robotics and Automation*, May 2013, pp. 3287–3292.

[18] J. A. Castano, Z. Li, C. Zhou, N. Tsagarakis, and D. Caldwell, "Dynamic and reactive walking for humanoid robots based on foot placement control," *International Journal of Humanoid Robotics*, vol. 13, no. 02, p. 1550041, 2016.

[19] V. Barasuol, J. Buchli, C. Semini, M. Frigerio, E. R. D. Pieri, and D. G. Caldwell, "A reactive controller framework for quadrupedal locomotion on challenging terrain," in *2013 IEEE International Conference on Robotics and Automation*, May 2013, pp. 2554–2561.

[20] M. Focchi, V. Barasuol, M. Frigerio, D. G. Caldwell, and C. Semini, *Slip Detection and Recovery for Quadruped Robots*. Cham: Springer International Publishing, 2018, pp. 185–199.

[21] S. Xin, Y. You, C. Zhou, and N. Tsagarakis, "Humanoid Running Based on Centroidal Dynamics and Heuristic Foot Placement," in *IEEE International Conference on Robotics and Biomimetics*, Macau, China, December 5–8 2017, pp. 2584–2590.

[22] S. Talebi, I. Poulakakis, E. Papadopoulos, and M. Buehler, "Quadruped robot running with a bounding gait," in *Experimental Robotics VII*. Springer Berlin Heidelberg, 2001, pp. 281–289.

[23] M. Kamedula, N. Kashiri, and N. G. Tsagarakis, "On the kinematics of wheeled motion control of a hybrid wheeled-legged centauro robot," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct 2018, pp. 2426–2433.