Summary of the Master's Degree Thesis (Sessione: 04/2024)

"Active suspension control for compliant wheeled locomotion on uneven terrain"

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1 Overview

Legged robots have been a focus of research in the field of robotics exploration given their ability to adapt and navigate a vast number of rough and unknown terrains. These systems are composed of multiple articulated legs which are responsible for the interaction with the environment, allowing for dexterous and independent movements. Nevertheless, achieving locomotion in such robots often necessitates intricate control strategies, which may require coordination with the dynamic of the entire robot and the activation of numerous motors, especially in highly redundant robots with a substantial number of joints per leg. On smooth surfaces, intricate mobility tasks can be simplified by integrating solutions like wheel locomotion. Incorporating wheels reduces the number of components that actively contribute to the planned movements, with a consequent decrease in energy consumption. When deploying a wheel-on-leg system on rough surfaces, a combined action of legs and wheels is expected. While the wheels will provide the needed propulsion, the legs can be actuated to cope with the disturbances and adapt the robot to the terrain deformities. However, developing a control strategy with this purpose could result challenging since these hybrid systems face difficulties in modelling and motion generation due to their overall complexity. Furthermore, the real-world environments where such robots are deployed are characterized by unstructured terrain and irregular profiles. When navigating these environments, the robot is subjected to disturbances in the form of external forces induced by the interactions with the ground. These disturbances have to be addressed through effective control design, limiting unstable movements, which could cause the tumble of the robot. These are the conditions where the robot CENTAURO is expected to operate. It is a highly redundant quadruped-on-wheels robot, designed in the Humanoid and Human Centered Mechatronics Lab of the Istituto Italiano di Tecnologia, which falls in the category of floating base system. Its structure is composed of an upper body, mainly applied to perform manipulation tasks through two articulated arms, and a lower portion accommodating the base and the articulated legs. The objective of the thesis is to develop a control strategy for the lower part of the robot, to execute wheeled locomotion on real-world terrains. In this sense, the legs will act as an active suspension system able to react in a compliant way against non-predicted changes in the terrain and adapt to the uneven surface to maintain contact with the ground for better stability of the robot. This approach will employ only proprioceptive sensors mounted on the robot, such as torque and IMU sensors, which provide information about the state of the robot, lacking any knowledge of the terrain conformation. Then, the controller will be tested both in real and simulated environments, Fig. 1, to assess its performance improvements.

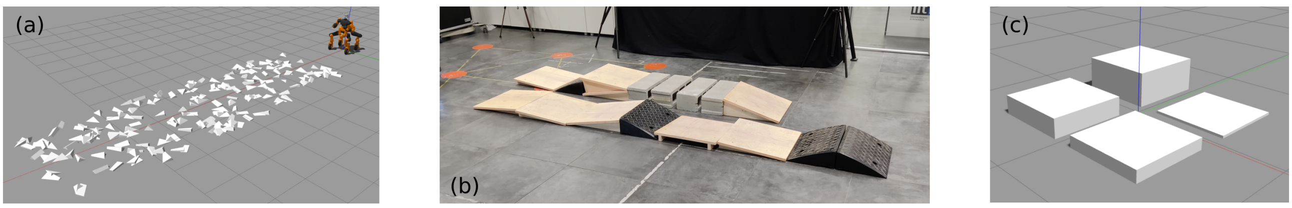

Figure 1: Environments used for tests: (a) and (c) for simulated rough terrain and height variations respectively; (b) for real-world testing in a laboratory environment.

2 Controllers Implementation

To implement this strategy, the design of two controllers is proposed to provide additional features to the already existing real-time framework developed for the robot: a Cartesian Impedance Controller (CIC) and an Attitude Controller (AT) on each leg. The CIC falls into the category of indirect force control and is used to model the dynamic of the limb's end-effector, such that it mirrors that of a virtual mass-spring-damper system along all the directions of the Cartesian space. The control input is represented by the error between a desired motion and the actual motion of the end-effector. In particular, if the interaction with the environment causes a manipulator to deviate from its desired position, it will generate a force proportional to this deviation, with the intent to restore the planned trajectory. This force-motion relationship is expressed as a second-order ordinary differential equation, where the parameters can be tuned to change the response behaviour. In addition to the force contribution of the mass-spring-damper system, a gravity compensation term is introduced to offset the gravitational force exerted by the robot's mass. Given the floating base nature of the robot, this force is distributed among all contact points, based on the center of mass (COM) position, resulting in an extra contact force component to be integrated into the dynamic of each leg. On the other hand, the Attitude Controller has been developed with the intent to dynamically change the reference values of the CIC to control the orientation of the base. The integration of the two controllers for each leg allows the robot to adapt to terrain with changes in altitude (e.g. slopes) while filtering the disturbances resulting from the interactions with the environment. Using data from the IMU sensor, the Attitude Controller is implemented through an impedance control mechanism for managing both Roll and Pitch angles between the base and the inertial frame. The primary objective is to maintain these angles as close to zero as possible, maintaining the base parallel to the ground plane. As the base joints cannot be directly actuated like other joints of the robot due to the system's floating base structure, the rotational motion associated with the control law of the Attitude Controller is mapped through geometrical relations into a corresponding vertical motion of each leg's end-effector. In Fig. 2 are reported the modules of the developed controllers.

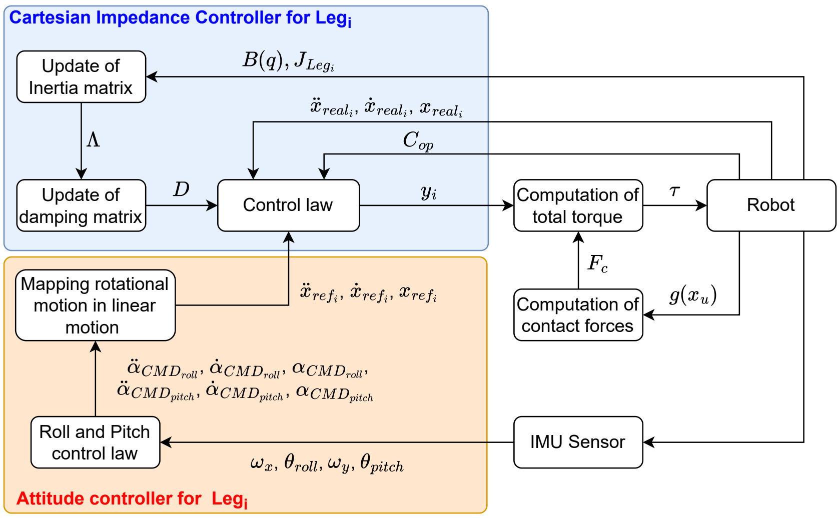

Figure 2: Diagram of the complete control framework

3 Results

First, the Cartesian Impedance Controller is tested alone to evaluate its effectiveness in improving CENTAURO's performance on challenging terrains, both in simulation and real-world scenarios, Fig. 1. The results obtained from the experiments demonstrated that the controller provides a stable response to the interaction with external stimuli. Even though whole-body dynamics were not considered in the implementation, the controller allowed the robot to cross rough terrain, maintaining contact with the ground, as reported in Fig. 5, and progressively reducing the base oscillation in more compliant configurations, as shown in Fig. 3. However, experiments on terrains with slopes revealed the controller's limitations in reacting to scenarios where the contact points of the legs experience significant height discrepancies due to the surface profile. The cause is mainly addressed to the controller's tasks to maintain a fixed configuration during navigation, thus tracking predetermined reference values. For this reason, the Attitude Controller is integrated into the overall framework. Through testing, it was observed that the Attitude Controller plays a crucial role in controlling the base orientation, particularly in terrain with changing altitude. Results indicated that configurations with higher stiffness in the Cartesian Impedance Controller tended to exhibit more stable response, particularly when coupled with non-critical damping in the Attitude Controller. Conversely, a more compliant behaviour led to increased oscillations and instability, underscoring the intricate relationship between the virtual systems. Moreover, the experiments conducted on terrains further demonstrated the effectiveness of the Attitude Controller in maintaining the base parallel to the ground, as shown in Fig. 4, where the angles value distribution significantly lower when the Attitude Controller is enabled. In conclusion, even though the stability is not guaranteed by specific strategies, the multiple contacts maintained by the Cartesian Impedance Controller, coupled with reduced oscillations, present a robust approach to improve the overall stability of the robot on rough terrain.

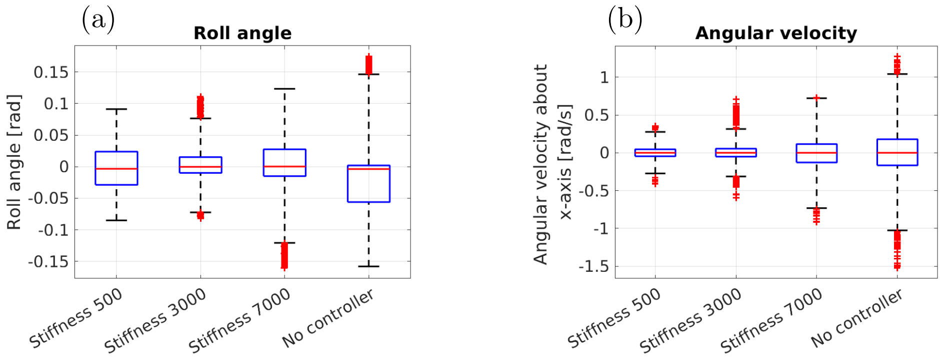

Figure 3: Values distribution of Roll angle (a) and angular velocity (b) resulting from experiments in a simulated environment. The reported stiffness setting refers to the value of the stiffness gain along the Z-axis motion of the Cartesian space set in the CIC and is expressed in N/m, The stiffness settings in the other directions are constant across the tests.

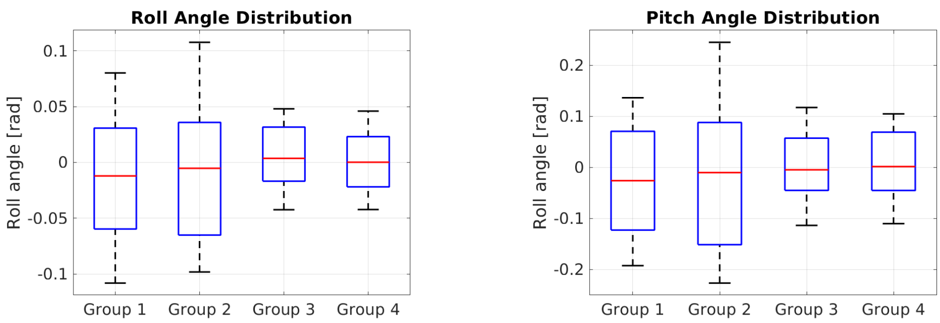

Figure 4: Resuting Roll and Pitch angle distribution from simulated experiments. Group 1: CIC set with stiffness 500 N/m, AT not enabled; Group 2: CIC set with stiffness 3000 N/m, AT not enabled; Group 3: CIC set with stiffness 3000 N/m, AT enabled, Group 4: CIC set with stiffness 7000 N/m, AT enabled

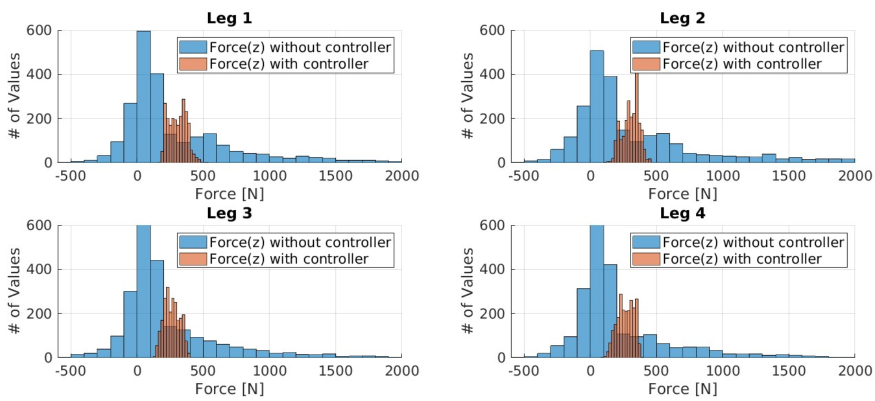

Figure 5: The reported forces represent the vertical component of the estimated contact wrench for each leg. The blue line refers to the case without the controller, while the orange line reports the forces when the controller is set with a stiffness of 500 N/m along the Z-axis. It is evident that with the controller enabled, the forces never go to zero.