I-RIM Conference 2019
October 18 - 20, Rome, Italy
ISBN: 9788894580501
DOI: 10.5281/zenodo.4814306

Towards Aerial Humanoid Robotics

Unifying Robotic Platforms for Manipulation, Aerial, and Terrestrial Locomotion

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Science fiction has long inspired pioneers of new areas of Engineering. When imagination meets the current needs of civil society, creative thinking then often gets real, and projects aiming at breakthroughs for advancing the scientific state of the art are put in place. Robotics is a scientific field that has always been driven by visionary applications of Engineering, often receiving impetus from the human will of having extended locomotion and interaction capacities.

The implementation of Manipulation and Locomotion on robotic platforms, however, remains a big challenge for the Robotics community. The resulting endeavor paved the way to new branches of Robotics aimed at combining Manipulation and Locomotion into single platforms. Aerial Manipulation [1], for instance, unifies Manipulation and Aerial Locomotion by conceiving robots capable of flying while manipulating an object. Humanoid Robotics [2], instead, merges Manipulation and Terrestrial Locomotion since humanoid robots can usually manipulate objects and move around by exploiting contacts with the environment (e.g. walking). This paper presents the challenges towards unifying Manipulation, Aerial, and Terrestrial Locomotion by implementing Aerial Humanoid Robotics. Aerial humanoid robots can then fly, walk, manipulate, and transport objects in the surrounding environment, thus being pivotal for disaster response and opening new branches of applications for humanoid robots.

In other words, Aerial Humanoid Robotics unifies Aerial Manipulation [1] and Humanoid Robotics [2]. By doing so, aerial humanoid robots overcome the lack of terrestrial locomotion of aerial manipulators and extend the locomotion capabilities of humanoid robots to the flight case. Aerial humanoid robots can then walk, fly, manipulate and transport objects, thus offering energetically efficient solutions to payload transportation and object manipulation. In fact, a platform implementing Aerial Humanoid Robotics can reach the desired location by flying, thus avoiding challenging terrains; once landed, the platform can move around by walking, and then manipulate objects while standing on two feet. Consequently, aerial humanoid robots are more robust and energetically efficient than classical aerial vehicles accomplishing manipulation tasks. Thanks to their terrestrial locomotion ability, aerial humanoid robots also avoid struggling with flying in confined spaces, where low altitude flight becomes tedious and energetically inefficient.

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Fig. 1: iRonCub in disaster response scenarios: video at https://goo.gl/2x5MzY

I. Theoretical challenges

A. Modelling of robot dynamics

By applying the Euler-Poincaré formalism to the humanoid robot yields the following equations of motion:

$$M(q)\dot{\nu} + C(q,\nu)\nu + G(q) = \begin{bmatrix} 0_6 \\ \tau \end{bmatrix} + \sum_{k=1}^{m} J_k^\top F_k, \quad (1)$$

where, M, C are the mass and Coriolis matrix, G is the gravity vector, τ are the internal actuation torques, $J_k = J_k(q)$ is a proper Jacobian. Here, the external forces are produced by the jet engines powering the humanoid robot.

In particular, we assume that the robot is powered by four thrust forces $T_1, T_2, T_3, T_4 \in \mathbb{R}$ acting along directions that are fixed to four robot links. We assume also that two of the four thrust forces are attached close to the robot shoulders (i.e. jet-pack). The other two thrust forces are kept close to the robot hands, and move accordingly to the robot end-effectors. Figure 2 depicts the jet configuration we are considering for the first experimental activities using a modified version of the iCub humanoid robot.

A fundamental assumption for control design is that each thrust force T_i is measurable, i.e. force sensors are installed in series with the turbo engines or measurements are obtained as outcomes of on-line external force estimation algorithms [3]. By defining $T := (T_1, T_2, T_3, T_4)^\top$, the effects of the thrust forces on the right hand side of the equations of motion (1) can be compactly written as follows:

$$\sum J_k^\top F_k = \sum J_k^\top(q)\, {}^{A}\imath_k(q) T_k := f(q, T). \quad (2)$$

Fig. 2: CAD of the iRonCub currently being produced

B. Control design

If we assume the four thrust forces T can be chosen at will, the equations of motion (1)- (2) are powered by $n+4$ control inputs. This in turn implies that controlling the entire robot configuration space $\mathbb{Q} = \mathbb{R}^3 \times SO(3) \times \mathbb{R}^n$, which is of *dimension* $n+6$, may not be straightforward being system (1)- (2) underactuated and thus not feedback linearisable.

Another route one may follow for the stabilization of system (1)- (2) is not to consider the entire configuration space, but one of its outputs (or tasks). A common task is be the stabilization of the robot momentum that allows us to give desired positions (i.e. center-of-mass) and influence the robot base orientation. The main problem here is that the rate-of-change of the momentum does not depend upon the (internal) joint torques τ but only on the four (external) thrust forces. Having four inputs in this dynamics, one cannot perform feedback linearisation of the six-dimensional dynamics.

1) An enabling assumption: Since the mass matrix $M(q)$ is positive definite (i.e. invertible) equations (1)- (2) point out that the joint dynamics $\ddot{s}$ can be feedback-linearized via a proper choice of the joint torques τ. So, any differentiable, desired joint velocity $\dot{s}_d \in \mathbb{R}^n$ can be stabilized with any desired settling time. We then make the following assumption.

Assumption 1. *The joint velocity $\dot{s} := u_2$ and the thrust forces rate-of-change, i.e. $\dot{T} := (\dot{T}_1, \dot{T}_2, \dot{T}_3, \dot{T}_4)^\top := u_1$, can be chosen at will and then considered as control inputs.*

2) Momentum and orientation control: Despite the aforementioned underactuation, Assumption 1 allows us to design controllers for both the robot momentum [4] or base orientation [5]. The performances of these controllers can be appreciated in the simulations shown in the following video

`https://goo.gl/2x5MzY`

C. Modelling of jet dynamics

Our approach to the characterization of model jet engines is based on a grey box model. In particular, preliminary experimental activities show that the dynamics of model jet turbines can be approximated accurately by a second order, nonlinear model characterized by a set of parameters K, i.e.

$$\ddot{T}_i = p(K, T_i, \dot{T}_i, u_i), \tag{3}$$

with u_i the i-th input of the jet turbine. This input is the duty cycle of a Pulse Wide Modulation according to the standard RC protocols. The set of parameters K characterizing the model (3) are identified during experimental campaigns.

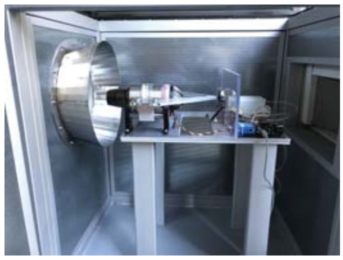

Fig. 3: The setup used for jet experimental campaigns

II. Practical Challenges

A. Robot CAD design

Figure 2 shows the CAD of the re-design of iCub for the flying application. One of the fundamental issues during this re-design has been the placement of the jet-turbines. Optimal locations of the jet-turbines have been the outcome of a co-design process, where we maximized the maneuverability of the robot at take-off conditions. The robot shown in Figure 2 is currently being produced and preliminary tests are expected in July 2019.

B. Experimental setup for jet identification

Figure 3 shows the setup used to perform experimental campaigns with jet turbines. Remark that these turbines have an exhaustion gas at about 800° Celsius, which however quickly vanishes around the turbines. The cones shown in Figure 2 (behind the robot) characterize the regions where the air is no longer harmful. However, the setup must be a chamber that can be closed, must be bullet proof to prevent injuries from turbine explosions, and fireproof. All these characteristics have been embedded in the setup shown in 3 that is used as identification test bed for the model (2). An example of experimental campaigns for model identification purposes can be seen at the following video

`https://www.youtube.com/watch?v=3kNqo5ZeT1w`

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