Francesco Nori

Research statement

Introduction

What: the focus of my research activities has been on motor control with two fundamental goals: studying humans and implementing humanoids. The achievement of these two goals is guided by two underpinning principles, which constitute the backbone of my research activities: a) studies on human motor control should be relevant for building better performing robots; b) implementing humanoids should contribute towards better understanding the human motor control system. The main technological outcome of my research activity is to endow humanoids with advanced action and interaction capabilities. The achievement of this goal necessarily passes through advancing the state-of-the-art within the following research areas in robotics: decisional autonomy [8, 10], dependability/adaptability [7, 14], perception [15] and, in a single all-embracing word, cognitive abilities.
Where: my research activity has significantly benefit from the unique interdisciplinary environment available offered by the Istituto Italiano di Tecnologia. In particular, my work has been deeply rooted in the activities of the Robotics, Brain and Cognitive Sciences department (Rbcs) on the one hand and the iCub Facility (iCub) on the other. Connections have been established and will be strengthen with the advanced robotics department (Advr), the pattern analysis and computer vision department (Pavis) and the rehab technologies laboratory (Rehab).
Who: the research achievements described and foreseen in this document have been and will be possible thanks to a talented and motivated team of collaborators. Our background is in engineering with strong competences in physics, mathematics and computer science.
How: two different tools are at the basis of my research. On the one hand, iCub is the technological tool that I personally contributed to develop [**1**]. On the other hand, control theory is the theoretical toolset, which scientifically grounds my technological implementations. In the attempt of combining theoretical and technological development, my research activity produces sound theoretical results validated with dependable implementations on real robots.

Methodology

Adopting a common subdivision in control theory, proposed implementations have required advances of the current state-of-the-art along three different areas: modelling, estimation and control. This subdivision is reflected in the following subsections, which give a systematic organisation to my recent research achievements.
Modelling: even though humans and humanoids are different in many aspects, part of my research activities aimed at finding abstraction levels at which they can be modelled with the same mathematical tools. Within this context, dynamics served to the physic laws that govern humans and humanoids motions, optimal control to model movement planning and compliance to model robustness against disturbances.

Dynamics. My research interest has been often focused on dynamics as opposed to kinematics. Dynamics allow capturing quantities, such as forces, which are fundamental for describing both action and interaction. As to this concern, the dynamics of humans

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and humanoids can be both modelled as articulated rigid bodies [Featherstone, 2007]. Indeed, despite of the underlying simplifications, articulated models have been proven to be quite effective in capturing the mechanics of humanoids [Vukobratovic et al., 2004] and the biomechanics of humans [Delp et al., 2007]. Dynamics can be therefore used as a common modelling tool capable of abstracting from specific differences (e.g. different geometries) while enforcing common mechanical principles (e.g. momentum dynamics).

Optimal control. Inspired by recent results on the role of optimality in human motor control [Flash and Hogan, 1985, Todorov, 2004], I have been investigating on the role of optimisation and optimal control as a tool for modelling movement planning in both humans and humanoids [12]. Leveraging on my previous works on inverse optimal control [16], I contributed to the problem of modelling arm reaching movements. Human experiments have shown that movement trajectories can be effectively predicted with the combination of multiple cost functions **[2]** while movement variability is best predicted by stochastic optimal control [6].

Compliance. In the attempt to find a common principle to explain the role of impedance regulation in humans [Burdet et al., 2001] and robots [Hogan, 1985], I investigated on the role of muscle co-activation as a mean to achieve robustness in action and interaction planning [9]. Despite of the significant delays in the human sensory-motor system, muscles seem to possess the interesting property of selectively and passively rejecting disturbances without explicitly resorting to active feedback. Intrigued by this experimental evidence, we were able to mathematically characterise this property [13] and to design a novel variable stiffness actuator capable of regulating its passive disturbance rejection via agonist-antagonist co-activation [11]. The physical realisation of the design principle in a working prototype **[3]** posed interestingly theoretical questions which significantly contributed to improving the original design principle itself. Further development of the design are foreseen in the near future.

Estimation: in order to improve robots interaction capabilities, they need to accurately perceive both internal and external forces: the former to control their movements and internal strains, the latter to regulate the interaction with the environment. Inspired by previous literature [Albu-Schäffer et al., 2007], I contributed to the design of a scalable set of sensors to make the iCub capable of regulating internal torques and interaction forces. Evaluating the trade-off between joint level and proximal force/torque sensing [18], the final adopted solution was the second. The technology allows to efficiently estimate the iCub whole-body dynamics **[4]** exploiting three primary sources of information: (1) embedded force/torque sensors, (2) embedded inertial sensors, (3) distributed tactile sensors (i.e. artificial skin). The methodology relies on a reordered recursive Newton-Euler algorithm, which meets the stringent computational-time constraints necessary for real-time applications [TFIN15]. Reframing the estimation problem in a Bayesian framework, the approach has been recently extended to include multiple redundant measurements [15], while keeping the computational complexity low by exploiting the problem sparsity [TKN15].

Control: most of my research activities eventually contribute to the final goal of implementing real-time whole-body controllers on the iCub humanoid. Given the iCub complexity, real-time applications call for stringent computational constraints which significantly limit the range of viable implementations. These constraints can only be met by adopting state-of-the-art solutions implemented in computationally optimised software for real-time solving complex non-linear optimisation problems.

Optimality and computational efficiency are common features for the controllers that I contributed to develop. The cartesian interface [17] is an example of a long-lived and efficient software capable of implementing an optimisation-in-the-loop strategy [Pat15]

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for performing on-line kinematic inversions. Similarly, the whole-body torque controller [**5**] implements a state-of-the-art inverse dynamic approach to solve the problem of force regulation in under-actuated but constrained mechanical systems. Simultaneous optimisation and computational efficiency are obtained by reframing the control problem as a quadratic programming optimisation [RPN15]. Exploiting the internal/external forces estimation strategy described previously, the controller has been successfully adopted in many different balancing tasks: single and double foot support, multiple noncoplanar contacts and constrained goal directed movements.

Research plan

As opposed to traditional robotic applications that demanded for limited interaction and mobility, robots of the next generations will be required to coordinate physical interaction with physical mobility. Interaction always involve two components: the "self" (i.e. the robot) and the "other" (i.e. the interacting agent). Successful and energetically efficient interaction necessarily passes through modelling, estimating and controlling the mutual interaction between the self and the other. In a crescendo of complexity, research is expected to cope with increasingly complicated scenarios. On the one hand, robots (the self) are foreseen to become elastic and compliant. On the other hand, physical interaction is likely to occur not only with rigid and compliant environments but also, on the long run, with humans. Gradually, robots will require advanced decisional autonomy, adaptability and the ability to understand the intention of "others". To cope with scenarios and embodiments of increasing complexity, my research pursue the methodology described above with focus on three main topics: modelling, compliance and control.
Modelling: as opposed to humanoids, humans control actions are mostly anticipative versus reactive. Anticipations require models that the agent should continuously adapt with experience [19, 20]. Following an idea already paved in my previous publications [7], my forthcoming research will investigate on the role of stochasticity to represent the uncertainties that inevitably affect models of reality. It is indeed one of my guiding principles to consider no model as perfect [15] and one of my ambitions to implement, on complex systems such as the iCub, control actions which optimally adapt to the uncertainties of acquired models [9].
Compliance: within this context, adjustable compliance is a promising direction to endow robots with the ability to cope with modelling uncertainties [7] and to control non-rigid interaction. In consideration of the augmented degree of under-actuation and complexity introduced with compliance, successful exploitation of compliance in whole-body motion motions require however significant theoretical and technological steps forward with respect to the current-state-of-the-art.
Control: finally, optimal control, in the form of model predictive control, seems to be the right direction to progressively endow robots with anticipative actions. My idea is to apply computationally efficient solutions [10] to cope with whole-body control. Advances in this sense are foreseen both at the theoretical (stability proof) [Mayne et al., 2000] and implementation levels (computational complexity) [Diehl et al., 2002].

Paper submitted as part of the evaluation package

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