Unifying the Control of Rigid Robots and Articulated Soft Robots

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I. INTRODUCTION

Articulated Soft Robots (ASRs), as shown in Fig. 1, represent one of the most significant evolutions in robot design in recent times [31, 32, 11, 9, 15, 12]. Their introduction was motivated by the desire to approach biological performance [7] by purposefully introducing elastic elements into the drive train to act as energy storage; these are of either constant [36] or variable impedance [42].

The interest in ASRs arises from the unique advantages compared to robots based on rigid mechanisms. Conventional industrial robots are fast and precise machines that excel at producing manufactured goods at an incredible throughput with high precision. Robots interacting with humans, however, have different requirements—”safety first” is the most critical design consideration, with accuracy being of secondary importance. Here ASRs shine as elastic elements dynamically decouple the actuator’s rotor inertia from the links during impacts [3, 45], thereby significantly reducing the potential for human injury [28, 29]. There are three major motivations to introduce compliant actuation: 1) inherent safety for human-centered robotics [3], 2) excellent mechanical robustness against impacts [43], and 3) energy storing capabilities enable highly explosive and/or efficient motions [4, 29, 8]. However, these advantages come at a price.

II. NEW TECHNOLOGIES BRING NEW CHALLENGES

Naturally, a paradigm shift in technology introduces new challenges. The implementation of a compliant physical structure enables the embodiment of safe and natural behaviors into a robotic system. However, the higher the actuator compliance, the more dominant the inherent oscillatory dynamics and the lower the control bandwidth [36, 18]. This is the price for the advantages above; a careful trade-off is required [44, 13, 10].

Spong and Ortega [38] list four structural properties of the rigid robot model that are most relevant for control purposes. Among these, it turns out that two fail for the ASR model: **P1**) There is an independent control input for each degree of freedom, and **P2**) the dynamics equations define a passive mapping between control inputs and link velocities. For ASRs P1 trivially fails, as the number of control inputs is (at least) twice the number of degrees of freedom, and neither is the mapping from inputs to link velocities passive [34]. This is the familiar problem of non-collocation of inputs and outputs that poses fundamental challenges for stabilization [33]. Interestingly, however, it turns out that P1 and P2 can be “recovered” for some systems, as discussed below.

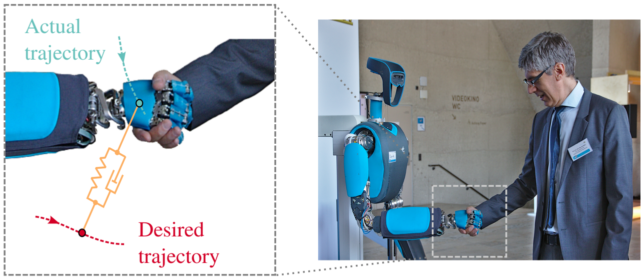

Fig. 1. Natural and safe human-robot interaction facilitated through the Cartesian impedance controller in [21] implemented on an ASRs.

III. RESEARCH OBJECTIVES AND CONTRIBUTIONS

The objective of my research is twofold. On the one hand, it aims to advance the control of underactuated systems. On the other hand, building on the results, I pursue the long-term goal of enabling robots to execute natural and efficient movements. Just think of the awe-inspiring performances of Olympic gymnasts, or the gracious and fluid movements of world-class ballet dancers. To accomplish this goal, I strongly advocate the utilization of compliant systems. The following sections summarize my contributions in this direction.

A. *Unifying the Control of Fully and Under-Actuated Systems*

The dynamic control of underactuated systems remains an ongoing challenge in control theory. We still lack general control principles that are practically applicable [26]. The crux is that many exciting problems in robotics belong to this class (soft robots, object manipulation, aerial, aquatic, and terrestrial locomotion) [39]. Motivated by this, I introduced the novel concept of *quasi-full actuation* (QFA) to *unify the control and analysis* of fully actuated systems and a general class of underactuated Lagrangian systems [24, 17]. The considered systems are characterized by the fact that they can be represented as the interconnection of actuated and underactuated subsystems, with the kinetic energy of each subsystem being only a function of its own motion. ASRs are typical representatives—and the main focus of my work.

The concept of QFA is based on a simultaneous coordinate and input transformation, on the extended phase space, that enables the considered class of underactuated systems to be treated as if they were fully actuated. Since the new inputs cannot be chosen entirely freely, the transformed system is referred to as quasi-fully actuated. Key aspects of the transforming equations are 1) both the original and transformed systems are characterized by the same Lagrangian function,

2) the transformed system defines a passive mapping between the new control inputs and velocities, and 3) the solutions of both systems are in a one-to-one correspondence and thus describe the same physical reality. This correspondence allows for the study and control of the behavior of the quasi-fully actuated system instead of the underactuated system. In other words, this novel approach allows the “recovery” of P1 and P2 and opens the door for the direct application of energy-based control techniques inherited from the fully-actuated case, while guaranteeing closed-loop system stability and passivity.

Research Question: *Is it possible to extend the concept of QFA to other classes of underactuated systems beyond ASRs?*

It is well-established that for collocated systems, the input-output (I/O) mapping is passive, readily allowing for robust stabilization using traditional control methods [5, 2]. With the QFA concept ”recovering” the collocation property, the transformed system’s implied I/O passivity presents a new pathway for robust control designs in underactuated systems [24, 17]. This raises the question of whether “modern” control techniques, such as reinforcement learning (RL), can also benefit from integrating the QFA concept.

Research Question: *When applied to underactuated systems, do RL algorithms similarly profit from the restored collocation of inputs and outputs by leveraging the concept of QFA? Specifically, it is worth investigating whether the training period can be shortened and whether more robust control designs can be obtained by utilizing QFA.*

B. A Minimalistic Control Approach for ASRs

By using the concept of QFA, a “*minimalistic*” control design can be pursued in the sense that the desired target behavior of the system is obtained by the least feedback modification of its dynamics [24, 17]; imagine the opposite spectrum of feedback linearization [37, 6]. Such an approach fits perfectly to underactuated ASRs for the following reason.

Experiences in the lab repeatedly revealed that control approaches that modify or override the intrinsic rigid robot dynamics to a significant extent tend to show unstable behavior on actual hardware . The higher the joint compliance, the lower the mechanical bandwidth [36, 1] and the more pronounced this issue becomes. This observation initiated the development of a series of passivity-based control schemes [19, 20, 16, 22, 21, 23, 24, 25, 30, 35, 14] for robots with elastic or viscoelastic joints that aim at minimizing the system shaping. “*Do as little as possible.*” These words summarize the design philosophy best. The underlying hope is that reducing the system shaping and having a closed-loop dynamics match in some way the intrinsic structure of the robot will award high performance with little control effort—with *natural motions being an emergent behavior*. Further, by minimizing the system shaping, we obtain low gain designs, which are favorable with regard to robustness. A comparison with state-of-the-art controllers in [17] highlights the minimalistic nature of the developed control designs.

Last but not least, two of my central works [21, 25] dispelled two common “misconceptions” of the community: 1) if passivity is desired, the renderable closed-loop stiffness is bounded by the joint stiffness of the SEA [41, 27], 2) rigid robots outperform elastic ones in terms of positioning accuracy. However, in [21], I showed that injecting load-side damping through the proposed controller and by considering the load port, instead of the standard spring port [40], results in less conservative criteria. In fact, any desired closed-loop stiffness can be passively rendered with the proposed controller—independent of a system’s joint stiffnesses. The result extends to systems with nonlinear elasticities [21] or elastic couplings [17]. Finally, the controller in [25] achieves a steady-state-error of $15\,\mu\mathrm{rad}$ on our VSA robot in Fig. 2, which is exactly the physical limit considering a position sensor resolution of 16 bits. This result highlights clearly that when it comes to positioning accuracy, rigid and elastic robots are potentially on equal footing.

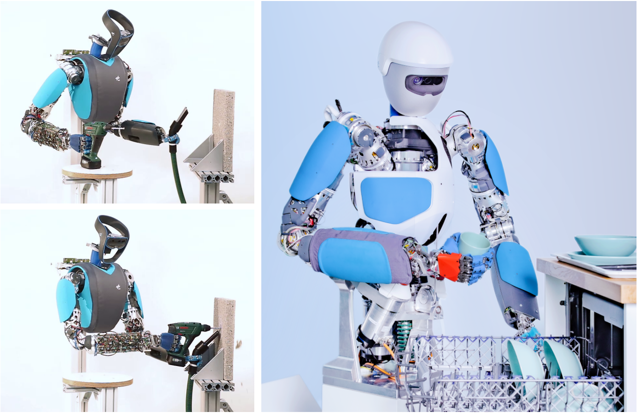

Fig. 2. The following demonstrations highlight the performance and robustness of a motion control framework based on my works [19, 16, 25]. (**left**) The elastic robot *David* is tasked to grasp a vacuum cleaner and drill hammer to bore a hole into a concrete plate. (**right**) An updated version autonomously unloads a dish washer, thereby relying on the high motion accuracy and careful interaction capabilities provided by the underlying control framework.

Research Question: *Robot design and control is usually a sequential process. However, in order to exploit the full potential of elastic systems, we must unify the mechanical and control design. Essentially, we must ensure that inertial, elastic and control forces harmonize and don’t fight each other. In this way only, can a controller be truly minimalistic in the absolute sense. How to achieve this?*

IV. CONCLUSION AND OUTLOOK

My motion control framework based on [19, 16, 25] enables our VSA robot in Fig. 2 to carry out commercially interesting tasks, including pick and place, teleoperation, drill-hammering into a block of concrete and unloading a dishwasher. The successful execution of such tasks demonstrates that compliant robots have a promising future in the commercial space.

In conclusion, soft robots excel in situations when highly dynamic contacts or collisions occur. In a future where robots are no longer afraid of impacts, but interact with humans and actively engage in contacting the environment, a predominant part of everyday robot assistants is likely soft.

ACKNOWLEDGMENTS

The realization of the demos on the VSA robot in Fig. 2 was a team effort by the many people involved in the development, maintenance and operation of the system.

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