A low cost Series Elastic Actuator Test Bench

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Abstract. The concept of compliance relates to a robot's capability to exert, absorb, and measure forces acting on its joints. The existing research currently available for compliant actuators is promising, but prohibitively expensive, posing a fiscal entry barrier to research.
This paper presents a low cost Series Elastic Actuator test bench, as an initial work towards a modular compliant actuator toolkit (MCAT).

Keywords: compliance · variable stiffness · series elastic actuator · robotics

1 Introduction

Traditionally, robots are of a rigid body design, where a motor is directly connected to a joint, to control its position. This makes them capable of repeatable precision, ideal for manufacturing applications. Compliant actuators differ in their ability to control both the position and the stiffness of a joint, which unlike rigid body robots, makes them more suitable for operating in a shared human-robot workspace. Different concepts feature different capabilities, including as impact absorption, energy storage, and natural motion generation [11].

To allow for further experimentation and exploration of this domain, we present our work on a series elastic actuator (SEA) test bench. For a wider engagement and to offer an entry point into the research domain, the test bench design will be made available online. Based on this, we then present our first steps towards a novel modular compliant actuator toolkit aimed for the usage in research as well as robotics education, before concluding the paper.

2 Background

In this section. we outline different approaches towards compliant actuators which motivate our work. On the topic of compliance methods in this paper, torque-sensing and virtual stiffness control is the only method to be considered mature and has been since 2008. By using a torque sensor to measure the force acting on a joint, and a sufficiently fast motor and controller, it is possible for a joint to respond fast enough to mimic the properties of a joint with a desired "virtual" stiffness [4]. No physical elastic element exists in the system, and thus there is no spring constant to be modified. Regarding control theory, a PID (proportional integral derivative) controller , with a set position and target stiffness suffices, a method also known as equilibrium stiffness control [5].

The technique was pioneered by the German Aerospace Center (DLR) during the 2000s [6] [13], has been commercialised by Kuka [2], and features in the leg mechanisms of many quadrupeds, with high bandwidth systems allowing them to respond to impacts and exert force [12]. Virtual stiffness control is comparatively easy to implement, but without a physical element, robots are denied many of the advantages of biological compliance, energy conservation, and explosive motions.

The concept of a series elastic actuator is straightforward. By placing a spring between the driving stiff actuator and the driven output joint, the force exerted on the spring can be measured. Equilibrium stiffness control is limited by the stiffness of the spring, but potential benefits include impact absorption and energy storage, as well as force control [8].

A series elastic actuator with a sufficiently soft spring can be used to absorb impacts in real-time with minimal computation, and to store and release energy. However, softer springs limit the bandwidth of the actuator, mandating faster motor and controller. This limitation spurred research towards torque sensing.

Variable stiffness actuators (VSAs) differ from prior methods in their ability to modulate the stiffness constant of a physical elastic element, such as a spring or tendon. Many methods to control the stiffness constant exist: the spring transmission ratio, structure controlled stiffness, and mechanically controlled stiffness. Further concepts such as agonist-antagonist non-linear spring pairs and artificial muscles also exist [7], but are beyond the scope of this early work [11] [12] [3].

The existing research in the domain consists almost entirely of one-off manufacturing [1], with compliance concepts designed either as part of the mechanical structure of the robot's arms, legs or other joints [13], or only as a bench test rig [9]. Much of the work from the previously described methods requires custom CNC machined parts, top-quality motors, sensors and computing parts. It follows then, that the existing research is prohibitively expensive to replicate. This problem compounds, in making it harder still to iterate ideas, make direct comparisons or investigate applications on the technology.

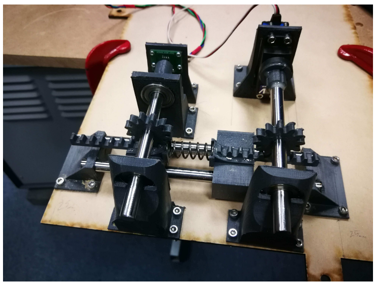

Fig. 1. SEA Test Bench: output shaft & encoder (left), driving shaft & servo (right)

3 Series Elastic Actuator Test Bench

To reduce the entry burden into compliance research through lower production costs, a test bench of a series elastic actuator (SEA) is presented, see Figure 1.

Out of the previously described compliance methods, the SEA was chosen for its design simplicity, which serves as our foundation for future work. This section outlines the SEA design & control and discusses manufacturing observations.

Design: A driving servo motor is connected in series to a compression spring, which in turn is connected to a driven output joint, as illustrated in Figure 2. An encoder reads the output joint position, and by measuring the difference between the two joints, the compression force acting on the spring can be determined using Hooke's Law.

All parts which were not purchased are 3D printed, with design tolerance included in the CAD models. The Fusion360 spur gear generator was used with a rack tooth pitch of $6.28mm$ derived from (1).

The Servo moment $m_t = 0.12kg/cm$ is calculated for a given servo $(10.1kg/cmat6v)$ and gear of radius of $0.012m$ using (2). Next, the moment is converted from kg/cm to a torque estimate in N/m of $m_t = 0.99N/m$. Finally, we rearrange for the linear force $F = 82.5N$ using (3).

Based on this max linear force estimate, an optimum spring is chosen. The $rs121 - 157$ datasheet specifies a load of $85.42N$ at minimum length, which closely matches the derived linear force estimate. A spring with greater deflection $(rs121 - 242)$ was considered, as a greater displacement would best visualise the SEA, but would be liable to buckle under compression unless incorporated into a piston.

$$Pitch_{Rackteeth} = \pi/Diameter_{Pitch} \tag{1}$$

$$m_t = 10.1kg/cm * radius_{gear} \tag{2}$$

$$Force = Moment/distance_{perpendicular} \tag{3}$$

Equilibrium Control: The ams5601 encoder is used for its high counts per revolution (2048), easy to use I^2C interface, and frictionless measurement of rotation from a radial magnet. A Nucleo-F429ZI microcontroller is used to implement PID equilibrium controlled stiffness of the SEA (*with its 180Mhz CPU it is not capable of real-time virtual stiffness control*).

3.1 SEA Test Bench Observations

The following consists of observations made during the design, manufacture and testing of the SEA test bench. It serves to inform the design of future work.

Smaller shafts, approximate to that of the motor shaft, should be used. The 8mm shafts are excessive and add inertia. Smaller shafts would also reduce the overall size, cost, and manufacturing difficulty. steel shafts of 4mm can be cut by hand with a junior hacksaw, 8mm shafts cannot.

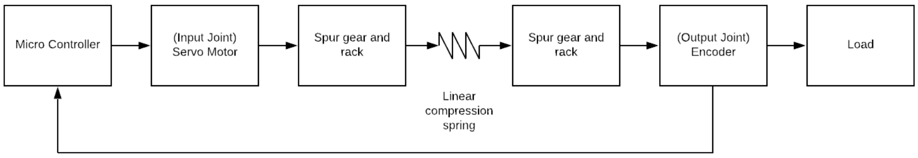

Fig. 2. SEA Test Bench block diagram

3D printing for structural supports and gears is viable. 3D printing for exact tolerances is not viable. So, while the rotational shafts free spin in their bearings the linear slide blocks do not glide without friction, as a result of the two linear shafts being out of alignment, itself caused by manufacturing deviations of the printed linear rail mounts. A linear rail guide rail should also be considered. Typically linear guide rails and carriages are more expensive, but low cost parts are available and should be tested.

The spur gear teeth profile size was too large, resulting in backlash that negated the otherwise reliable precision of the sensor. In the future, helical gears with smaller teeth will remedy this. When accounting for this imprecision, the test bench is able to accurately estimate spring compression forces and can control for a desired stiffness setting.

Non-backdrivability of the input joint is a common requirement for control schemes to measure the force exerted on the spring. In practice, a worm screw is typically used to achieve this non-backdrivability [10]. Sans worm screw, and when a force overcomes the stall torque of the servo, and the force applied becomes two components; spring deflection, and input joint position error. This feature should be included in future as an option for different use cases.

4 Future Work

The series elastic actuator test bench is the first milestone towards the development of a low cost modular compliant actuator toolkit (MCAT). The MCAT concept trades size and material quality in favour of manufacturing cost, and facilitates easy reconfiguration and modification, for the experimentation of a wide variety of variable stiffness concepts. The MCAT is intended for a variety of use cases such as the integration into the knee joint of bipedal humanoid robots, research into the design and application of different variable stiffness actuator (VSA) concepts. To allow for wider dissemination, the project files are to be made freely available for the robotics community. The first MCAT prototype should be designed as an optimisation of the SEA test bench, realising a series elastic actuator in a low cost and easy to use unit.

5 Conclusion

In this paper, the need for a low cost compliant actuator is identified, for use in academic research and education. We present a series elastic actuator test bench that is used to help inform design choices for future work, towards a modular compliant actuator toolkit. This work is offered to the robotics community during these early stages of development to garner feedback that will guide the direction of future work.

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