From Series Elastic Actuation to Series-Parallel Elastic Actuation

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Published in:
Actuator14: Proceedings International Conference on New Actuators

Publication date:
2014

From Series Elastic Actuation to Series-Parallel Elastic Actuation

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Abstract:
Actuators are key components for moving and controlling a mechanism or system. However, the torque to weight ratio and the energy efficiency of the current state of the art actuators is much lower than in human muscles. As a consequence, among others, manipulators for human robot interaction in industry or service applications have a low payload to weight ratio and low energy efficiency. Therefore, we developed a novel actuation concept which we name Series-Parallel Elastic Actuation (SPEA). The concept enables variable recruitment and locking of multiple springs in parallel. After a problem analysis, the Series-Parallel Elastic Actuator schematic will be introduced. Next, our two prototypes will be discussed. The experimental results endorse the practicability of the SPEA concept and the modeled trend of a lowered motor torque and increased energy efficiency.

Keywords: Energy efficiency, torque to weight ratio, compliant actuation, load cancellation

1 Introduction

Servomotors are generally used for industrial robots as they make the joint's mechanical impedance very high, often considered as infinite, so they are ideal for precise tracking with a high bandwidth. As a consequence, however, industrial robots are unsafe for working in unstructured environments and to interact with humans. Therefore, robots mostly operate in a safeguard space secured by cages or safety light curtains and sensors.

Future robots will, however, strongly collaborate with humans, implying new requirements with regard to robustness and safety. Manipulators for assistance technologies in industrial settings (also referred to as co-workers) are currently being developed by several of the leading robotics companies. Moreover, they are already being implemented in pilot plants in the automotive industry. Robustness and safety requirements for human-robot interaction can be met by either active or passive compliance. Active compliance is based on joint torque sensing and is therefore limited by the controller bandwidth [1]. Passive compliance is based on the actuator architecture itself by means of a compliant element in series with the load and the motor [2] [3]. It was introduced by the Series Elastic Actuator (SEA) of Pratt et al. [4]. Two decades of research later various Variable Stiffness Actuators (VSA) and Variable Impedance Actuators (VIA) are developed. A recent overview by Vanderborght et al. can be found in [5]. Compliant actuators can, furthermore, store and release energy over the spring which can potentially lead to more energy efficient systems [6].

Future robots will not only colaborate with humans in a robot cell, but will also become mobile in order to operate a diversity of tasks in the whole factory [7]. The energy-efficiency and torque-to-weight ratio of current manipulators is, however, inadequate and therefore we developed a novel actuation concept which we name Series-Parallel Elastic Actuation (SPEA) [8] [9]. The concept enables variable recruitment and locking of multiple springs in parallel. After the problem analysis in section 2, the SPEA concept and experimental results of the first 2 prototypes will be discussed in section 3. Section 4 concludes the paper.

2 Problem analysis

Multiple manipulators for human-robot interaction are recently being developed in research projects or are already commercially available. A non-exhaustive list of recent examples is shown in Table 1. It includes manipulators driven by both stiff and compliant actuators. Mekabot's A2 compliant robot arm and Rethink Robotics' Baxter are one of the first commercialized manipulators which are driven by SEAs. The low torque-to-weight ratio of current stiff and compliant actuators results in low payload-to-weight ratios of these manipulators, compared to a ratio of 1 for a sound human (indicated in Table 1). Moreover, humans can for example walk for days while the best humanoids run quickly out of batteries. Also human dexterity is, for example, still not met by robotics applications.

On the other hand, however, the average specific power density and energy efficiency of a mammalian skeletal muscle (0.05 W/g) is an order of magnitude lower compared to electric motors (0.5 W/g) [10]. The maximum energy efficiency of an electric motor (>80%) is also higher compared to a muscle (<40%). Despite this higher power density and maximum efficiency, the electric motors are not

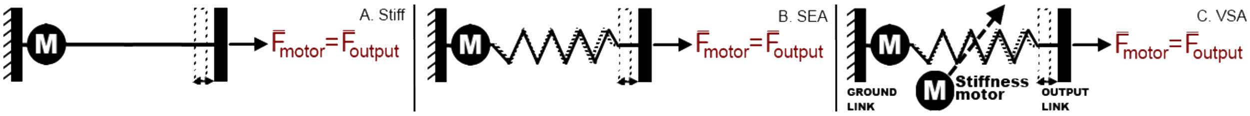

Fig. 1:*From A to C: linear schematics of a stiff actuator, a SEA and a VSA. In either a stiff actuator, a SEA or a VSA the motor force is always similar to the output force since the load is always in series with the motor.*

yet able to better actuate mechatronic systems than a biological muscle. This makes us conclude that the way transmissions and springs are used needs fundamental research.

Table 1 *Comparison of the payload to weight ratio of recent manipulators with stiff of compliant actuators*

Stiff actuators	
ABB's dual arm concept FRIDA	2x0.5kg / 20 kg
Universal Robots UR5	5kg / 18.4kg
Yaskawa's SDA robots	5kg / 110kg
Kawada NextAge	2x1.5kg / 28kg
Kuka lightweight LWR4+	7kg / 16kg
Kinova's Jaco and Mico	1.5kg / 5kg
Compliant actuators	
Mekabot's A2 compliant robot arm	2kg / 11.3kg
Bionicrobotic's BioRob robot arm	4kg / 17kg
Rethink Robotic's Baxter	± 2.6kg / 19kg

As we described in previous work [8] [9], we believe the main problem is the fact that in either a stiff actuator, a SEA or a Variable Stiffness Actuator (VSA), the full output load always stresses the motor since motor and load are in series. This is indicated in Fig. 1 where the three linear schematics indicate that indeed the output force is equal to the force which loads the motor $F_m = F_o$. Furthermore, robot joints typically require high torques at low speeds. As a result, high reduction ratios are required since DC motors typically work at high nominal speeds and low nominal torques. The gearboxes then become heavy and inefficient since the energy losses and weight increase with the number of stages. High torque DC motors are also heavy since the weight of DC motors increases linearly with the maximum continuous output torque [11]. Furthermore, the quadrant of low speed and high torque is the most inefficient quadrant in the energy efficiency contour of DC motors. Therefore, DC motors in robotics often work below their maximum efficiency since the iron losses are in quadratic relation with the current which is in linear relation with the motor torque. In general, one could state that the low torque-to-weight ratio and low energy efficiency of current actuators are limiting the performance of novel robotic applications.

3 The SPEA concept and prototypes

Based on the problem analysis of section 2, we developed a novel actuation concept which we name Series-Parallel Elastic Actuation (SPEA). The concept enables variable recruitment and locking of multiple springs in parallel, for which every spring can be contracted and locked over the joint, one after the other, by an intermittent mechanism. As shown in Fig. 2, each parallel spring is connected with one side to the output link. The other side of each spring is connected to the output of one of the parallel dephased intermittent mechanisms. An intermittent mechanism converts a continuous (rotational) input to 2 consecutive phases [12]:

1) Motion phase: the output is actuated by the input.
2) Dwell phase: the output is blocked while the input rotates freely.

Each parallel spring of the SPEA can be either in unpretensioned phase, pretensioned phase or pretensioning phase. Since each spring can be locked in its pretensioned and unpretensioned position, the motor will only feel a fraction of the total output torque.

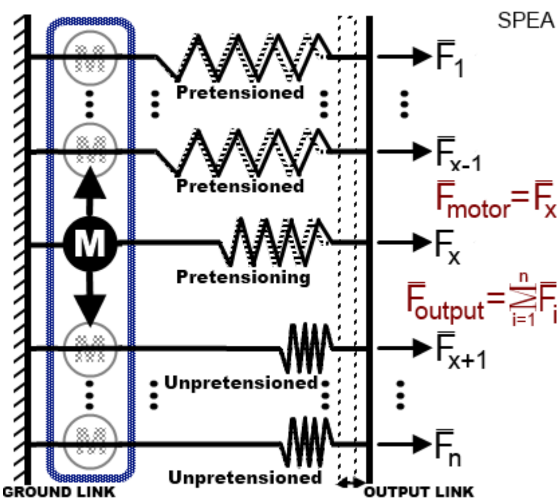

Fig. 2 *The schematic of the SPEA with n parallel springs. The dephased intermittent mechanisms are represented by the blue dotted rectangle.*

Fig. 2 shows a schematic of a SPEA with n dephased intermittent mechanisms and springs in parallel. The motor (circle in solid black) can successively switch position (circles in dashed gray) by means of the intermittent mechanisms. When the motor is turned over a certain limit, the spring in the pretensioning phase will go to the unpretensioned or pretensioned phase, and the next spring will enter the pretensioning phase. The dephased intermittent mechanisms can be developed based on different mechanical principles.

3.1 First SPEA prototype: mutilated gears

The first SPEA prototype consists of 4 parallel springs which deliver a uni-directional output torque. Four pairs of dephased mutilated gears with locking ring in parallel are used as an intermittent mechanism. Fig. 5 shows a picture and a 3D drawing. The pairs of mutilated gears are shown on the right and the output drums on the left. Each mutilated gear consecutively tensions one of the four parallel springs from singular position over 180° to the next singular position.

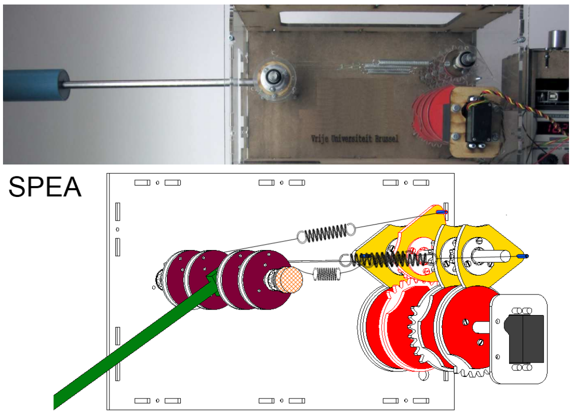

Fig. 3 *A picture and 3D drawing of the first SPEA prototype based on mutilated gears as an intermittent mechanism.*

The motor torque and power experiment on our first prototype are shown in Fig. 4. The experiment aims to show the lowered motor torque and power of the SPEA compared to an equivalent stiff actuator and SEA. In Fig. 4 the respective motor torques are plotted as a function of the output angle of each actuator. The output is connected to a gravitational load of 0.26 kg at 0.3m which will be lifted to its horizontal position at 90°. Since the output torque is in sinusoidal relation to the output angle, the motor torque of the stiff actuator is a sinus. The motor torque of the SEA has a comparable maximum, since both actuators are serial set-ups. The modeled SPEA motor torque is clearly lower than both serial set-ups. The measured SPEA motor torque approximates the model. The total torque produced by the pretensioned springs rises and equals the total output torque when all springs are tensioned and locked. The motor power experiment consists of lifting a load and performing a sinusoidal between 70° and 90°. The motor current and voltage are measured, resulting in the motor electric power. Due to the variable load cancellation the motor power of the SPEA with 2 springs is clearly lower than for the stiff actuator. The SPEA with 4 springs decreases the motor power even more. As a result, the SPEA with 4 springs only requires 11% of the energy required by the stiff actuator, while performing the same task.

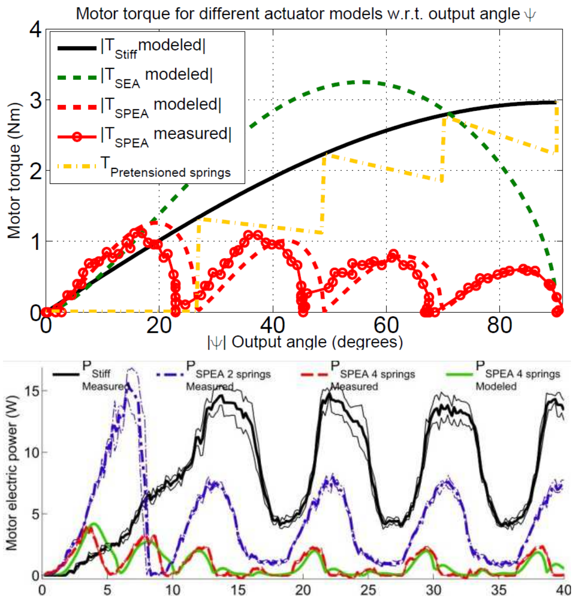

Fig. 4 *The motor torque and power measurements of the first SPEA prototype match the modeled trend of reduced motor torque and power compared to an equivalent stiff actuator and SEA.*

3.2 Second SPEA prototype: MACCEPA based with self-closing mechanism

The second SPEA prototype is based on the MACCEPA actuator which is developed in our lab. [13]. By combining the virtues of the MACCEPA actuator and the SPEA concept, the second SPEA prototype enables bi-directional output torque, variable stiffness and a relatively compact design [14]. The self-closing mechanism consists of a guide and a tensioner. The guide is designed as such that the tensioners are locked automatically when the motor arm pushes the tensioner to the end of the guide. When the motor arm moves in the reverse direction, it unlocks the tensioner automatically and the spring can be tensioned in the other direction. The four parallel springs are arranged as such, that the middle equilibrium position is reached when 2 springs are locked on one side of the guide and 2 springs are locked on the other. The maximum torque in each direction is then reached when the springs are all locked on one side of the guide. The results are submitted for IEEE/RSJ IROS 2014 (in review).

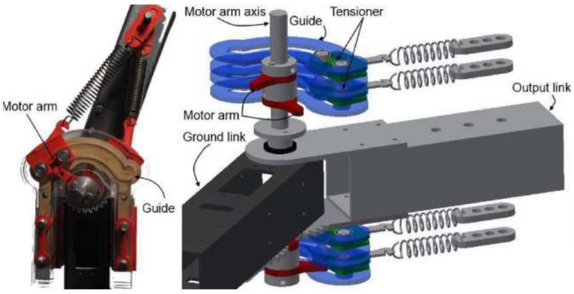

***Fig. 5** A picture and a 3D drawing of the second SPEA prototype which is based on the MACCEPA actuator and uses self-closing guides as an intermittent mechanism.*

4 Conclusion

This paper discusses the future challenges for robotics and identifies the low torque-to-weight ratio and energy efficiency of current actuators to be two major problems to be solved. The SPEA concept is then introduced and discussed together with 2 prototypes which are based on 2 different intermittent mechanisms which enable the variable load cancellation. The experiments verify the potential of the SPEA concept which will be further elaborated in the future.

5 Acknowledgement

This work has been funded by the ERC-grant SPEAR (no. 337596).

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