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MACCEPA-based Series-Parallel Elastic Actuators (SPEA) for the next generation of robotic co-workers

Glenn Mathijssen[1], Raphaël Furnémont, Dirk Lefeber, and Bram Vanderborght

***Abstract*— Robots are still outperforming humans regarding their efficiency and dexterity. On the other hand, however, muscles are more efficient and have a higher power to weight ratio than electric motors. As a consequence, among others, manipulators for human robot interaction in industry or service applications have a low payload to weight ratio and a 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. In this paper the latest MACCEPA-based SPEA is presented and first results are shown.**

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 human-robot interaction and are positioned in cages or secured by safety light curtains and sensors. The next generation of robots will strongly collaborate with humans, implying new requirements such as safety and energy-efficiency. For example manipulators for assistance technologies in industrial settings, also known as co-workers, are currently a vastly emerging technology. Multiple manipulators, of which some are listed in Table I, are being developed in research projects or are already commercially available. Mekabot's A2 compliant robot arm and Rethink Robotics' Baxter are rather exeptional in Table I since these are the first commercialized manipulators which are driven by complaint actuators, also known as Series Elastic Actuators [1].

The limited torque to weight ratio of current actuators, stiff or compliant, however limits the payload to weight ratio of these manipulators. This can be seen from Table I. On the contrary, the average specific power density of a mammalian skeletal muscle (0.05 W/g) is an order or magnitude lower compared to electric motors (0.5 W/g) [2]. 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 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. As we described in previous work [3] [4] 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.

For these reasons, 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 [4]. Fig. 1 shows a MACCEPA-based SPEA with 4 parallel layers with a self-closing mechanism. The actuator is based on the variable stiffness actuator MACCEPA actuator (the Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator) which is designed in our group [5]. Each layer converts a continuous (rotational) input to 2 consecutive phases [6]:

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

TABLE I

Comparison of the payload to weight ratio of recent manipulators with stiff or compliant actuators.

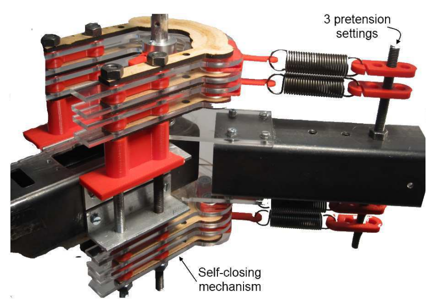

Fig. 1. A picture of the MACCEPA-based SPEA with 4 self-closing layers.

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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. The dephased intermittent mechanisms can be developed based on different mechanical principles [6]. In [7] [4], for example, we used so-called mutilated gears with a locking ring as an intermittent mechanism. In the MACCEPA-based SPEA of Fig. 1 a self-closing mechanism is used.

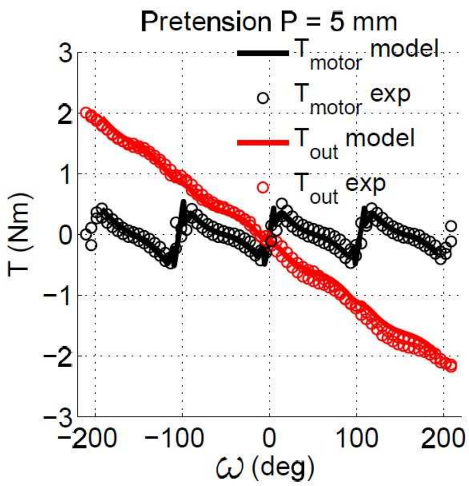

Fig. 2. Due to the variable load cancellation, the motor torque is approximately 4 times lower than the output torque.

Fig. 2 shows that the modeled SPEA motor torque is clearly lower than the generated output torque. Furthermore, the measured SPEA motor torque approximates the model. By changing the pretension, the stiffness of the joint can still be changed as for a traditional MACCEPA actuator.

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