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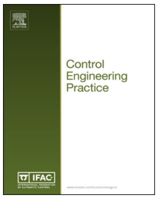

Practical relevance of faults, diagnosis methods, and tolerance measures in elastically actuated robots

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ABSTRACT

Elastically actuated robots promise safe human–robot interaction and energy-efficient motions. Yet, increased complexity and critical operation states might increase the practical fault risk. This paper explores faults in such robots using expert data from the field and identifies components that show increased fault occurrence: the highest fault sensitivity occurs in kinematics, electronics, sensors, and software. Since elastic actuators are an active field of research, few cases of industrial application exist and thus most experts in this study have academic background. Beyond assessing fault sensitivity, countermeasures such as redundant design are compiled. A brief literature review discusses fault diagnosis and fault-tolerant design with respect to these insights. Despite the availability of a few promising methods in robotics, neither diagnosis nor tolerance do receive sufficient recognition leaving potential for practical application.

1. Introduction

Increasingly close human–robot interaction recently leads to a rising relevance of elastic designs in robotics (Haddadin, De Luca, & Hirzinger, 2008; Lens & von Stryk, 2012; Park, Lee, Song, & Kim, 2008). A promising application of soft robots is industrial working environments where they support human workers. To ensure the safety of those, elastic characteristics enable the robots to react by deformation in case of contact (Haddadin et al., 2008; Lens & von Stryk, 2012). Further applications are found in assistive and rehabilitation robotics for motion assistance in prostheses (Au, Weber, & Herr, 2009; Holgate, Hitt, Bellman, Sugar, & Hollander, 2008) and ortheses (Müller, Pott, & Schlaak, 2012) as well as motion training (Lünenburger, Colombo, Riener, & Dietz, 2004; Schmidt, 2004). Besides an improved human–robot interaction, elastic actuation can reduce power requirements and increase energy efficiency by adapting actuator elasticity to the task-specific requirements (Vanderborght, Van Ham, Lefeber, Sugar, & Hollander, 2009), e.g., by matching natural dynamics of the robot and trajectory frequencies (Beckerle, 2014; Beckerle, Wojtusch, Rinderknecht, & von Stryk, 2014).

Motivated by those possibilities, various actuator concepts incorporating fixed or variable elasticity have been proposed (Vanderborght et al., 2013). If aiming at safe human–robot interaction, a serial elastic element that introduces a compliant coupling between the drive and link side is usually integrated. Thus, contact with external loads can be taken by deformation to decrease the risk of harming humans. This concept was first introduced by the Series Elastic Actuator (SEA) (Pratt & Williamson, 1995) and the Mechanical Impedance Adjuster (MIA) (Morita & Sugano, 1995) in the middle of the 1990s. In SEA, the physical stiffness is fixed but virtually modified by control while the joint stiffness of MIA can be varied by changing the length of the elastic element. A variety of Variable Stiffness Actuators (VSA) with different principles to vary physical stiffness has been proposed meanwhile and the topic remains subject to active research (Vanderborght et al., 2013). Generally, faults in elastic actuators and countermeasures to treat such are not sufficiently investigated up to now since focus of most publications is set on modeling, design, and control, e.g., in Hurst, Chestnutt, and Rizzi (2004), Jafari, Tsagarakis, Vanderborght, and Caldwell (2010), Kim and Song (2012), Beckerle et al. (2013) and many others.

This paper aims at exploring which faults are most common in elastic actuators, understanding how relevant faults are for practical application, and what are possible countermeasures. Section 2 analyzes background and challenges in modeling, design, and control of elastic actuators. A discussion of challenges emerging from those aspects motivates the deeper investigation of faults. Therefore, a questionnaire survey with participants from international robotics research in academia and industry is presented and evaluated using descriptive statistics in Section 3. Considering these results from the field and a brief literature review, the suitability of fault diagnosis methods and approaches to fault-tolerant design are discussed in Section 4. A final conclusion is given in Section 5.

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2. Background and challenges

Subsequently, background and challenges in modeling, design, and control of elastically actuated robots are described.

2.1. Modeling

Exemplarily, mechanical model of a serial elastic actuator is shown in Fig. 1. In mechatronic design as well as motion and force/torque control of robots using elastic actuators, a crucial challenge is coping with the nonlinear dynamics of robotic systems. Neglecting friction, those are modeled by:

$$\begin{aligned} &\mathbf{M}_l(\mathbf{q}_l)\ddot{\mathbf{q}}_l + \mathbf{C}_l(\dot{\mathbf{q}}_l, \mathbf{q}_l) + \mathbf{G}_l(\mathbf{q}_l) + \mathbf{K}_s(\mathbf{q}_l - \mathbf{q}_a) = \mathbf{0}, \\ &\mathbf{J}\ddot{\mathbf{q}}_a - \mathbf{K}_s(\mathbf{q}_l - \mathbf{q}_a) = \boldsymbol{\tau}_a, \end{aligned} \tag{1}$$

in the serial elastic case according to Spong (1987) and Albu-Schäffer (2002). In the multi-link case, the torques $\boldsymbol{\tau}_a$ are introduced by actuators and effect positions of links and actuators that are denoted by $\mathbf{q}_l$ and $\mathbf{q}_a$, respectively. Position-dependent inertial effects due to the links that are given by $\mathbf{M}_l(\mathbf{q}_l)$, Coriolis and centrifugal effects modeled by $\mathbf{C}_l(\dot{\mathbf{q}}_l, \mathbf{q}_l)$, and gravitational ones denoted as $\mathbf{G}_l(\mathbf{q}_l)$ can introduce nonlinear effects. Link and drive dynamics are coupled by the elastic torque represented by the product of the serial stiffness matrix $\mathbf{K}_s$ and the relative motion $(\mathbf{q}_l - \mathbf{q}_a)$. Inertial effects of the actuators are represented by $\mathbf{J}$. For Parallel Elastic Actuators (PEA) as those applied in Mettin, La Hera, Freidovich, and Shiriaev (2009) and Grimmer, Eslamy, Gliech, and Seyfarth (2012), the dynamics are modeled by:

$$[\mathbf{M}_l(\mathbf{q}_l) + \mathbf{J}]\ddot{\mathbf{q}}_l + \mathbf{C}_l(\dot{\mathbf{q}}_l, \mathbf{q}_l) + \mathbf{G}_l(\mathbf{q}_l) + \mathbf{K}_s(\mathbf{q}_l) = \boldsymbol{\tau}_a, \tag{2}$$

since actuator and link are rigidly coupled and thus $\mathbf{q}_l = \mathbf{q}_a$ while the other end of the spring is fixed to ground.

2.2. Design

In (variable) elastic actuator design, crucial practical issues are stiffness implementation and possibly principles for stiffness modification. In Van Ham, Sugar, Vanderborght, Hollander, and Lefeber (2009), variation mechanisms are categorized as equilibrium-controlled, structure-controlled, mechanically controlled, and antagonistic-controlled stiffness. Among those, the latter three are categorized as actuators with physically adaptable compliance (Vanderborght et al., 2013). On the contrary, equilibrium-controlled actuators change their apparent stiffness properties virtually by means of control (Vanderborght et al., 2013). Beyond stiffness and its variation, the configuration of elastic elements and actuators has significant impact on dynamics and energy efficiency of elastic actuator concepts (Beckerle, 2014; Beckerle et al., 2014). Besides SEA and PEA topologies, serial–parallel elastic configurations exist (Mathijssen, Furnemont, Van Ham, & Vanderborght, 2014). As dynamic properties like inertial or gravitational effects significantly impact the natural dynamics of elastic actuators (Beckerle, 2014; Beckerle et al., 2014), a precise characterization and modeling is crucial to exploit their natural dynamics.

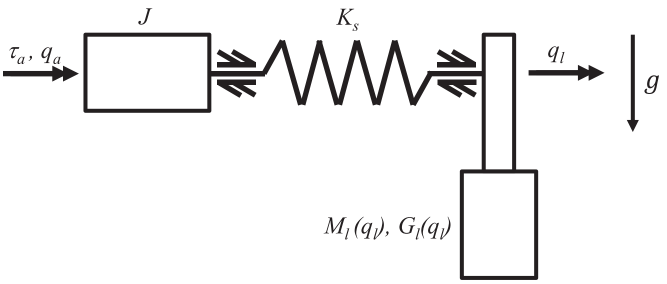

Fig. 1. Mechanical model of a single-link robot with elastic actuation in serial configuration.

2.3. Control

Due to the nonlinear control issue, model-based methods are frequently applied to meet requirements of stability, accuracy, robustness or load adaptation (Ozgoli & Taghirad, 2006). Non-model based approaches like PID-control (proportional, integral, derivative) are mostly combined with model-based methods since those consider system characteristics and thereby enable operation in states without collocation (Ozgoli & Taghirad, 2006). Hence, elastic actuators can be operated in or close to its natural or anti-resonance modes with such methods to reduce power consumption and increase energy efficiency (Beckerle, 2014). The majority of model-based motion control techniques for robots with elastic joints are based on feedback linearization methods (Spong, 1987), singular perturbation theory (Spong, Khorasani, & Kokotovic, 1985), and the passivity principle (Ott, 2008). While earlier works usually consider joint flexibility as an unwanted effect, more recent ones interpret it as a technical potential in terms of human-safety and/or efficiency. All of these approaches can also be used for force/impedance control to additionally alter elastic behavior by control (Spong, 1989).

2.4. Motivation to investigate faults

Beyond common issues in design, control, and implementation, challenges that are not observed in non-elastic robotics occur: while the latter represent a long-established technology, robots with elastic actuators are researched since the 1990s (Pratt & Williamson, 1995) and not used in industrial/commercial applications too frequently. Hence, practical experience and knowledge in terms of fault probability and severity is rather low but important as such applications emerge recently, e.g., elastically actuated robot manipulators[1] and foot prostheses.[2] Specific challenges that should be analyzed and addressed with respect to faults in practical applications are:

- The integration of elastic elements goes along with higher system complexity. This is even more pronounced in variable elastic actuators that include a second drive train to modify stiffness properties during operation. Due to the higher number of components and their integration, the possible number of faults might increase.
- In some applications, elastic drive trains are utilized to exploit natural dynamics for improved energy efficiency, velocity, or comparable criteria, e.g., Beckerle (2014) and Haddadin, Huber, and Albu-Schäffer (2012). By this, elastically actuated robots are operated in potentially critical states with increased control requirements (Erler, Beckerle, Strah, & Rinderknecht, 2014) that might increase the chance of fault occurrence.

As both challenges result in a higher risk that is defined as the product of fault probability and severity (Isermann, 2006), fault diagnosis and fault tolerance are promising approaches to increase the reliability of elastically actuated robots generally and especially in critical operations. These positive impacts on reliability might also increase human safety as a main objective of elastic actuation. Similar to state-of-the-art internal combustion engines (Isermann, 2010), comprehensive diagnosis and appropriate countermeasures

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[1] http://www.bionic-robotics.de/, http://www.rethinkrobotics.com

[2] http://www.biom.com/, http://www.springactive.com/