# Technical faults in elastically-actuated robots

## Expert opinions and methodological analyses

Robotic systems using elastic actuators provide safe human-robot interaction and energy-efficient operation. Since increased complexity and critical operation states could foster fault occurrence, this paper investigates faults in elastically-actuated robots. To identify and assess relevant faults, expert opinions from an online survey are statistically evaluated and methodological analyses are performed considering a practical example. A variable torsion stiffness actuator is therefore examined by a function and structure analysis that feeds a failure mode and effects analysis. Beyond confirming the results of previous studies, the analyses in this paper substantiate the potential relevance of faults in the elastic elements and that faults might have crucial effect on human-machine interaction in general. From a methodological perspective, failure mode and effects analysis appears very suitable for fault analysis in systems engineering.

**KEYWORDS** Fault diagnosis / failure mode and effects analysis / elastic actuators / robotics.

**Technische Fehler in Robotern mit elastischen Aktoren – Experteneinschätzungen und methodische Analysen**
Robotersysteme mit elastischen Aktoren ermöglichen eine sichere Mensch-Roboter-Interaktion und einen energieeffizienten Betrieb. Da steigende Komplexität und kritische Betriebssituationen das Auftreten von Fehlern begünstigen können, untersucht der vorliegende Beitrag technische Fehler bei Robotersystemen mit elastischen Aktoren. Um relevante Fehler zu identifizieren und zu bewerten, wurden Expertenaussagen aus einer Onlinebefragung statistisch ausgewertet und zudem methodische Analysen an einem Praxisbeispiels durchgeführt. Hierzu wurde ein Aktor mit variabler Torsionssteifigkeit einer Funktions- und Strukturanalyse unterzogen und deren Daten für eine Fehlermöglichkeits- und -einflussanalyse genutzt. Die vorliegende Arbeit bestätigt zum einen die Ergebnisse früherer Studien. Darüber hinaus untermauert sie die praktische Relevanz von Fehlern in den elastischen Elementen und deutet darauf hin, dass Fehler im Allgemeinen entscheidende Auswirkungen auf die Mensch-Maschine-Interaktion haben können. Aus methodischer Sicht, erscheint die Fehlermöglichkeits- und -einflussanalyse für die Fehleranalyse im Systemengineering sehr geeignet.

**SCHLAGWÖRTER** Fehlerdiagnose / Fehlermöglichkeits- und -einflussanalyse / elastische Aktoren / Robotik

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Currently, an increasingly close human-robot interaction drives the importance of elastic robot designs [1, 2, 3]. Elastic robots have significant potential to ensure the safety of human workers in industrial environments because they deform on contact [1, 3]. Moreover, they are promising for application in assistive and rehabilitation robotics [4, 5, 6]. Additionally, elastic actuators can improve energy efficiency by adapting actuator stiffness to the task [7]. To this end, the natural dynamics of the robot can be tuned to comply with the trajectory frequencies [8, 9].

In the recent decades, this potential has led to the development of a variety of actuator concepts with fixed or variable elasticity [10]. Such actuators can facilitate safe human-robot interaction [11] and improve energy efficiency [9]. First concepts such as the Series Elastic Actuator (SEA) [12] and the Mechanical Impedance Adjuster (MIA) [13] rely on an elastic coupling of drive and link. More recently, various elastic actuators based on different architectures with either fixed or variable physical stiffness have been proposed [10]. However, faults in elastic actuators do not appear to have received adequate attention [14] and few specific studies have been conducted [15, 16].

This paper extends the exploration of faults in [14] using additional expert survey data and methodological analyses of a Variable Torsion Stiffness (VTS) actuator [17, 16]. The additional questionnaire responses from international experts in robotics research improve the reliability of fault relevance investigation. The results of the renewed descriptive analysis are given in Section 1. In section 2 Function and Structure Analysis and a Failure Mode and Effects Analysis (FMEA) of the VTS actuator are presented. This is followed by a discussion of the results and conclusions.

## 1. EXPERT OPINIONS

While elastic actuators have been a topic of robotics research since the 1990s [12, 13], they are still not frequently used in industrial/commercial applications [14]. This affects practical experience of fault probability and severity although such knowledge could be of distinct importance because elastic actuators exhibit increased system complexity and might lead to higher control requirements [18, 14]. Hence, the possible number of faults as well as the possibility of fault occurrence might increase. To cope with this, fault diagnosis and fault tolerance methods could be helpful, e.g. such described in [19]. By surveying expert opinions, this paper aims at improving the knowledge of faults in elastic actuators. The subsequent evaluation focuses on the fault probability of specific components and fault relevance in general.

### 1.1. Survey and evaluation methods

The applied questionnaire consists of thirteen items and three open questions [14]. Three items survey the participants' profession and technical information, i.e. actuator-elasticity configuration and variable stiffness implementation according to [20]. An open question asked about operating hours, and nine items asked for the frequency of faults in components of the elastic actuators. The survey differentiated between structural/mechanical components (abbreviated MECH, e.g. shafts, couplings, housings, etc.), bearings (BEAR), gearboxes (GEAR),

**TABLE 1:** Fault occurrence rating scale

| Option | Occurrence |
|---|---|
| Very often | > 1 in 10 h |
| Fairly often | 1 in 10 – 100 h |
| Sometimes | 1 in 100 – 10; 000 h |
| Seldom | < 1 in 10; 000 h |
| Never | 0 |

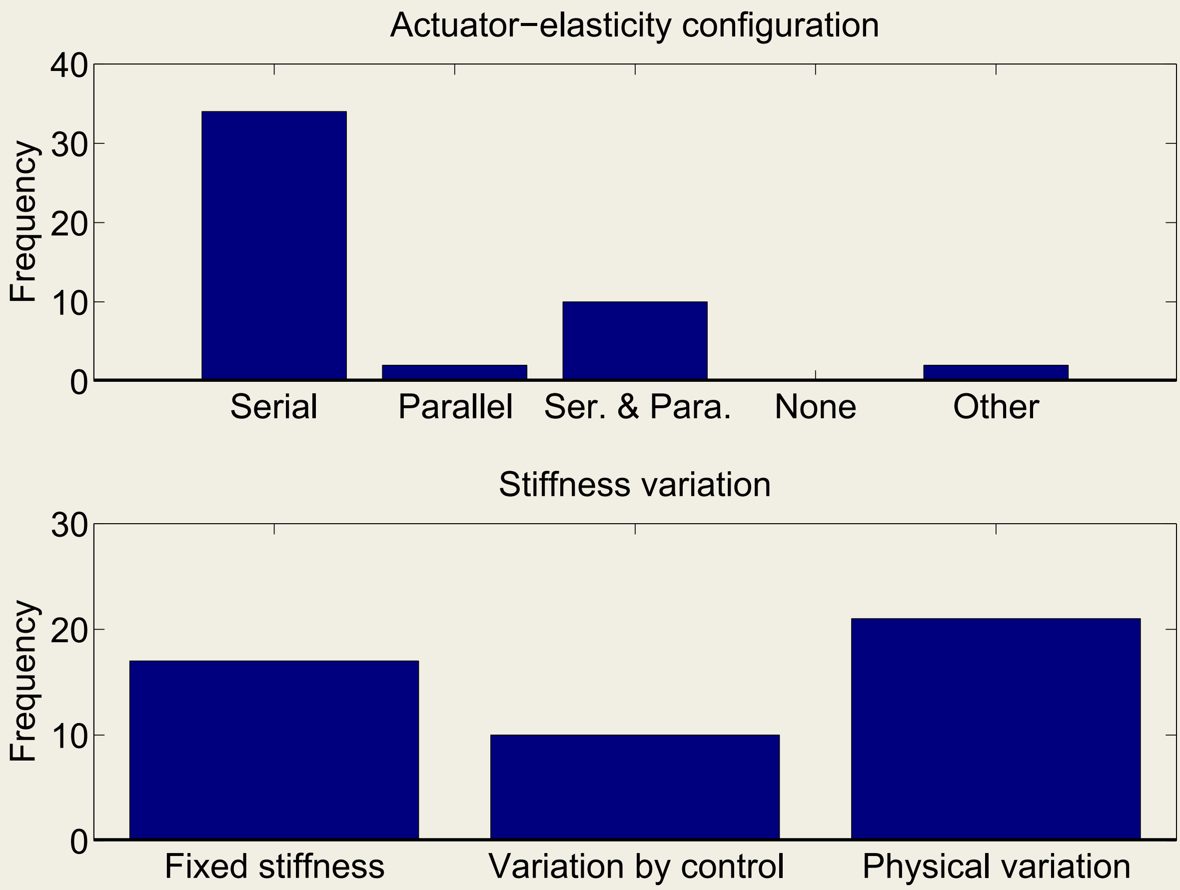


**FIGURE 1:** Frequencies of actuator-elasticity configurations and stiffness variation implementations

elastic elements (ELAS, e.g. springs, elastomers, etc.), kinematic components (KINE, e.g. linkages, pulleys, cam disks, cables, etc.), actuators (ACTU, e.g. DC motors, pneumatic cylinders, etc.), electronic components (ELEC, e.g. microcontrollers, motor controllers, etc.), sensors (SENS, e.g. encoders, force transducers, etc.), and software (SOFT, e.g. embedded control algorithms). Participants were asked to assess fault occurrence using a five point scale as shown in Table 1. The large range of operating hours reflects the fact that elastic actuation is still mostly applied in robotics research. Two open questions collected information about highly fault-sensitive components and counter measures that are practically applied by the participants. The final item asked for a general assessment of how relevant faults in elastic actuators are from a practical perspective. The relevance could be rated to be “very high”, “high”, “neutral”, “low”, or “very low”.

Participants were acquired by personal contacts to distinguished (soft) robotics experts and an invitation via the robotics worldwide newsletter. After two acquisition phases during the preparation of [14], additional participants from research and industry were contacted to prepare this study.

Descriptive statistic analyses of the questionnaire data were performed using Matlab R2014a. Professions of the participants and technical information about the actuators were analyzed regarding frequency. We evaluated means, standard deviations, and the corresponding box plots for the nine fault occurrence items and the final item concerning the practical relevance of faults. For the interpretation of box plot data, faults with a clear trend towards ratings below 4 were assessed to be of practical relevance [14]. As such faults would occur more than every 10,000 operating hours, they are assumed to appear more often than other faults in technical systems considering common literature [19, 14]. The

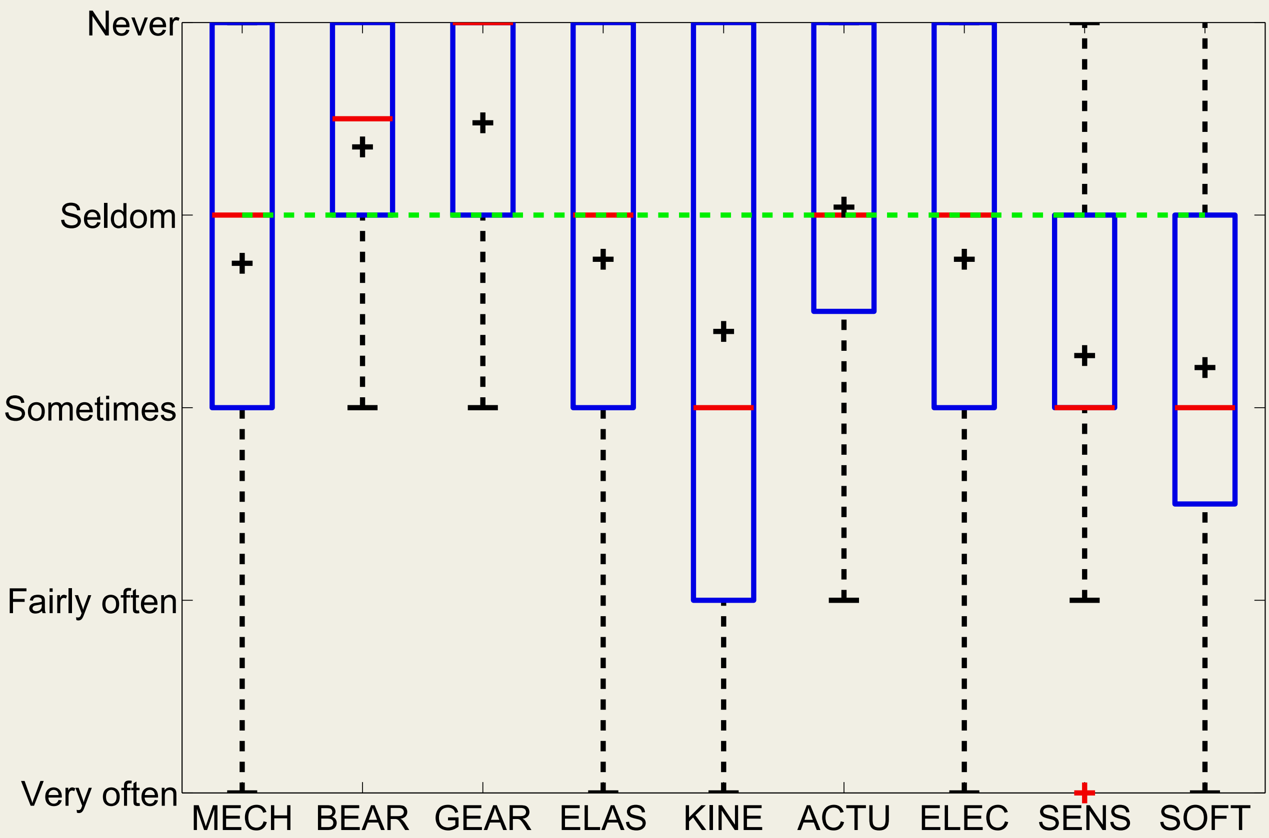


**FIGURE 2:** Box plot of responses to items assessing fault occurrence

open question regarding fault sensitivity is evaluated using the tag cloud generator of tagcrowd.com with default options.

### 1.2. Professions and technical information

All 51 participants who anonymously completed the questionnaire responded to each numerical item. Three responses were excluded because the participants used non-elastic actuators. Among the remaining 48 experts, some did not answer all open questions. The participants included 16 professors, 9 postdoctoral researchers, 12 PhD students, 4 engineers from academia, 5 engineers from industry, and 2 participants stating "other". As mentioned above and observed in [14], the majority of experts have an academic research background, since elastic actuators are rarely used in industrial applications. However, the responses are assumed to give practically relevant ratings due to the experimental experience of the participants [14]. Figure 1 shows the actuator-elasticity configurations and stiffness variation techniques reported by the experts, which are comparable to those in [14]. Most actuators are series elastic (34), while only two are exclusively parallel elastic, 10 combine both, and two belonged to "other" categories. Stiffness is fixed in 17 actuators while 10 vary apparent elasticity by control and 21 exhibit physical stiffness modification mechanisms.

### 1.3. Fault relevance and component sensitivity

Figure 2 shows the box plot of the responses on fault occurrence in the specific technical components. Means and medians of the responses are represented by black crosses and red lines, respectively. The range between the 25th and 75th percentile comprising the second and third quartile of the data are indicated by the blue boxes. Black whiskers mark the most extreme data points not considered outliers (red crosses) by the software.

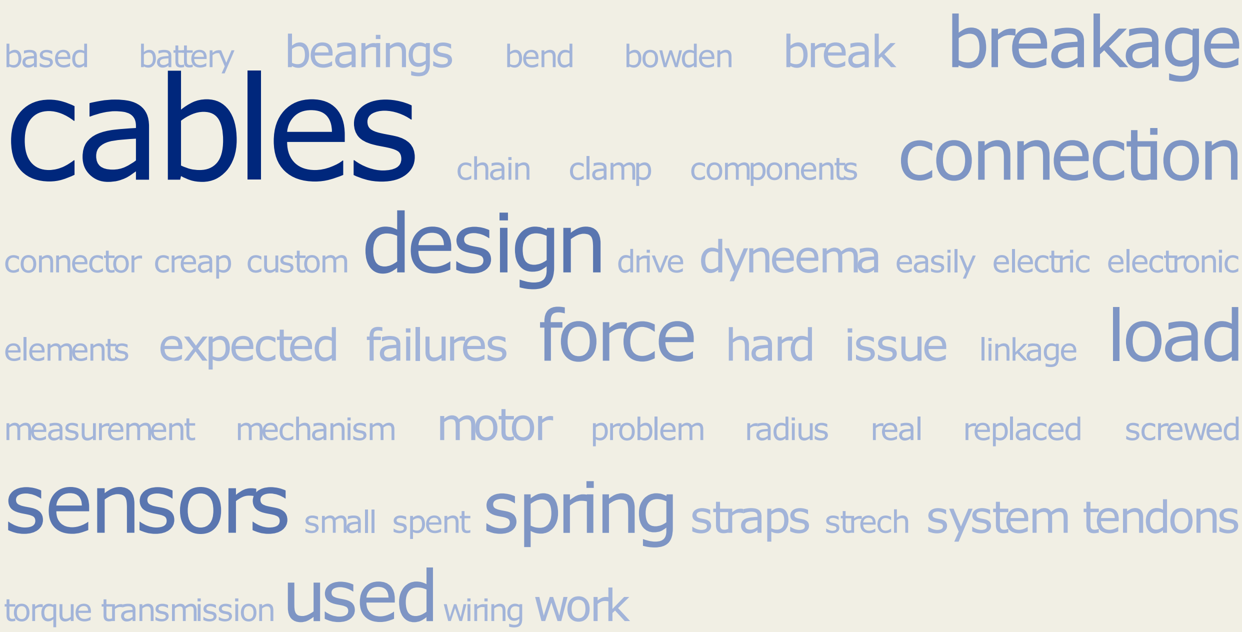


**FIGURE 3:** Tag cloud of responses to the open question asking for sensitive components

The whiskers in Figure 2 indicate the rather high spread of response data already observed in [14]. Still, the number of operating hours stated by the participants are highly differing and generally low but should facilitate an exploration of fault relevance regarding the individual components. Despite slight changes compared to [14], off-the-shelf components appear uncritical, i.e. bearings (BEAR), gearboxes (GEAR), and actuators (ACTU). Although the assessment of the mechanical components (MECH) and elastic elements (ELAS) is still spread around 4, slight trends towards increased relevance can be observed. This supports the interpretation of [14], that these components might be relevant. Although ratings of the kinematics (KINE) are spread wider, the relevance of these components is confirmed. Faults in sensors (SENS) retain a rather high occurrence probability and those relating to electronics (ELEC) are confirmed at the threshold. A distinct change is observed in the assessment of software (SOFT) faults which appeared to be of very high relevance in [14] but receive ratings similar to KINE and SENS in this study.

The tag cloud in Figure 3 confirms the relevance of kinematic and electrical components as well as sensors. Additionally, the rather high frequency of "spring" underlines the interpretation that elastic elements seem relevant. As in [14], mechanical and electrical connections as well as contacts are mentioned rather often.

Figure 4 shows the general assessment of practical fault relevance. Compared to the previous study [14], the trend towards high ratings is underlined. The median increases from "neutral" to "high" while mean and second and third quartile lie between those ratings.

## 2. METHODOLOGICAL ANALYSES

The questionnaire results indicate which components of elastic actuators are prone to faults. For a more in-depth analysis of faults in elastic actuators and their effects, a VTS actuator is considered as a practical example. This sheds light on how fault diagnosis and fault-tolerant design might be used and which methodological approaches are suitable.

For a systematic assessment of faults and their impacts on the VTS actuator, a Function and Structure Analysis (FSA) and a Failure Mode and Effects Analysis (FMEA) [21, 22] were conducted by a mul-

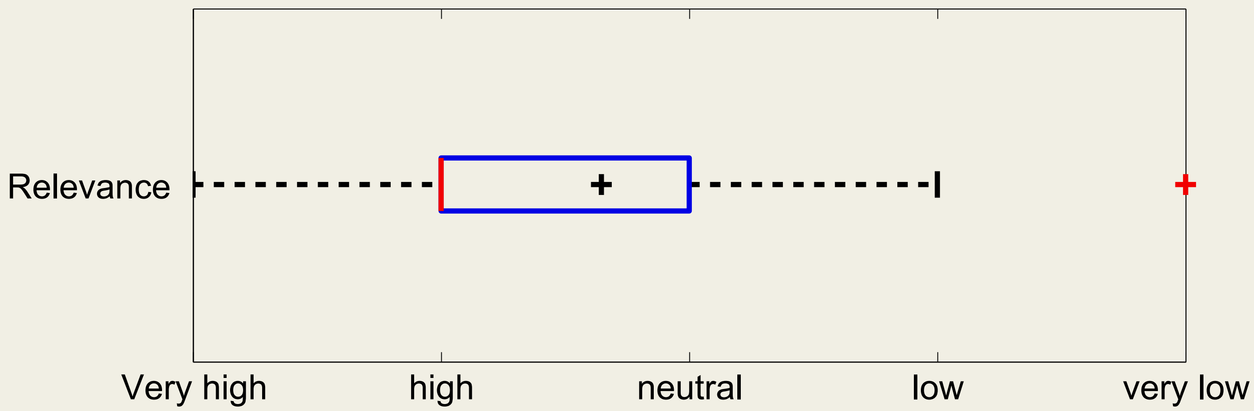


**FIGURE 4:** Box plot of responses regarding the practical relevance of faults

ti-disciplinary group of six experts recruited from the faculties of mechanical engineering, computer science, and sports science of Technische Universität Darmstadt, Germany.

### 2.1. Variable torsion stiffness actuator

As a practical example, the VTS actuator introduced in [17] is considered. Functionally, VTS changes the physical actuator stiffness by altering the active length of a torsion spring.

A prototype VTS actuator is presented in Figure 5. The lower actuator gearbox unit drives the joint, while the upper one sets stiffness through a ball screw mechanism. A pendulum serves as the load and the torsional elastic element is realized by a polyoxymethylene rod in serial configuration. To provide the torques of the lower actuator to the pendulum, a relocatable brass slider connects the elastic element to the slitted tube that is located around it [17].

Both actuators and the link are equipped with optical motion encoders.

### 3.2. Function and structure analysis

After briefing the experts about the function and setup of the VTS actuator, a structure analysis was conducted to determine inter-dependencies between the components. The edges of the resulting graph were extended by information about the function of the components. Due to the high granularity of the analysis, Figure 6 depicts a distinctly reduced representation of the non-directed, combined function and structure graph. The VTS system is divided into the lower actuator that drives the joint, the elasticity, the load, and the stiffness adaptation mechanism. The details of the complete graph serve as the basis for the subsequent FMEA. It includes 62 elements (nodes) connected by the corresponding functions (edges).

### 2.3. Failure mode and effects analysis

FMEA represents a formalized method to analyze failures and minimize the impacts of faults in systems engineering [21, 22]. It guides the identification of severe and critical faults and components that have high impact on the system reliability and safety. The risk of particular failures can be characterized by the risk priority number (RPN) which is the product of fault severity, probability, and detection rate [19].

The graph resulting from the FSA was pre-analyzed by the whole expert group yielding a starting point for an in-depth FMEA. The functions of the elements are assigned to the components actuator, load, elasticity, and stiffness adaptation from the FSA. Furthermore, human-machine interaction (HMI) was added to consider possible applications where elastic actuators operate closely with human users. Fault severity, probability, and detection rate were rated by the two experts from mechanical engineering using a scale ranging from 1 (low, uncritical) to 10 (high, critical). Rating tables specifying the assessment criteria were developed by the technical experts, e.g. verbalizing how function is affected (severity) or if components are off-the-shelf or custom-built parts (probability).

Figure 7 summarizes the RPN values of the elements in a box plot, categorized in the corresponding function classes. In view of the close interaction of human and actuator, many failures yield very high

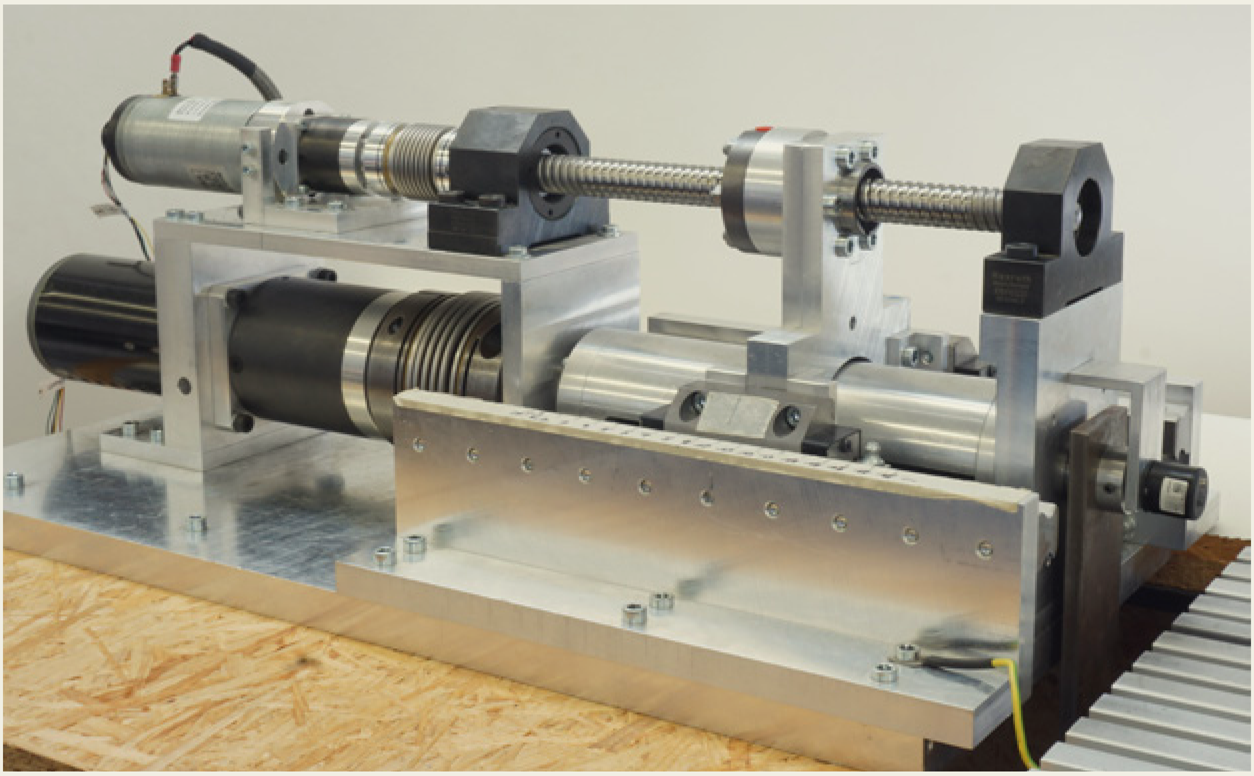

**FIGURE 5:** Variable torsion stiffness actuator

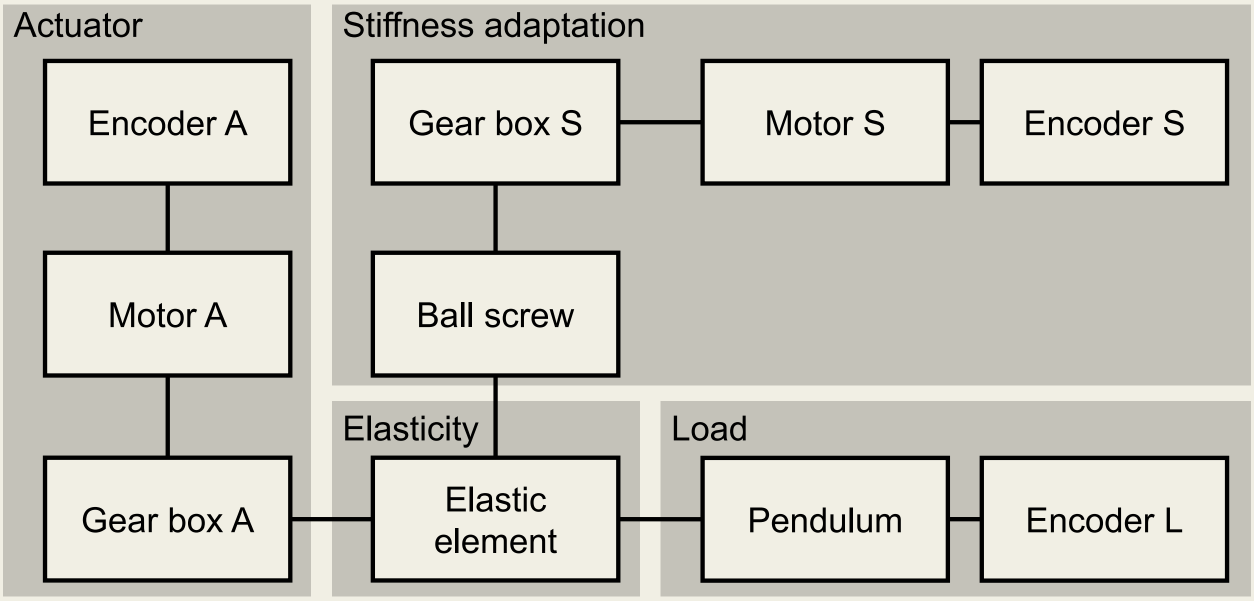


**FIGURE 6:** Reduced functional and structure graph of the VTS actuator. Edges indicate moving connections of the drive train elements. The housing is excluded

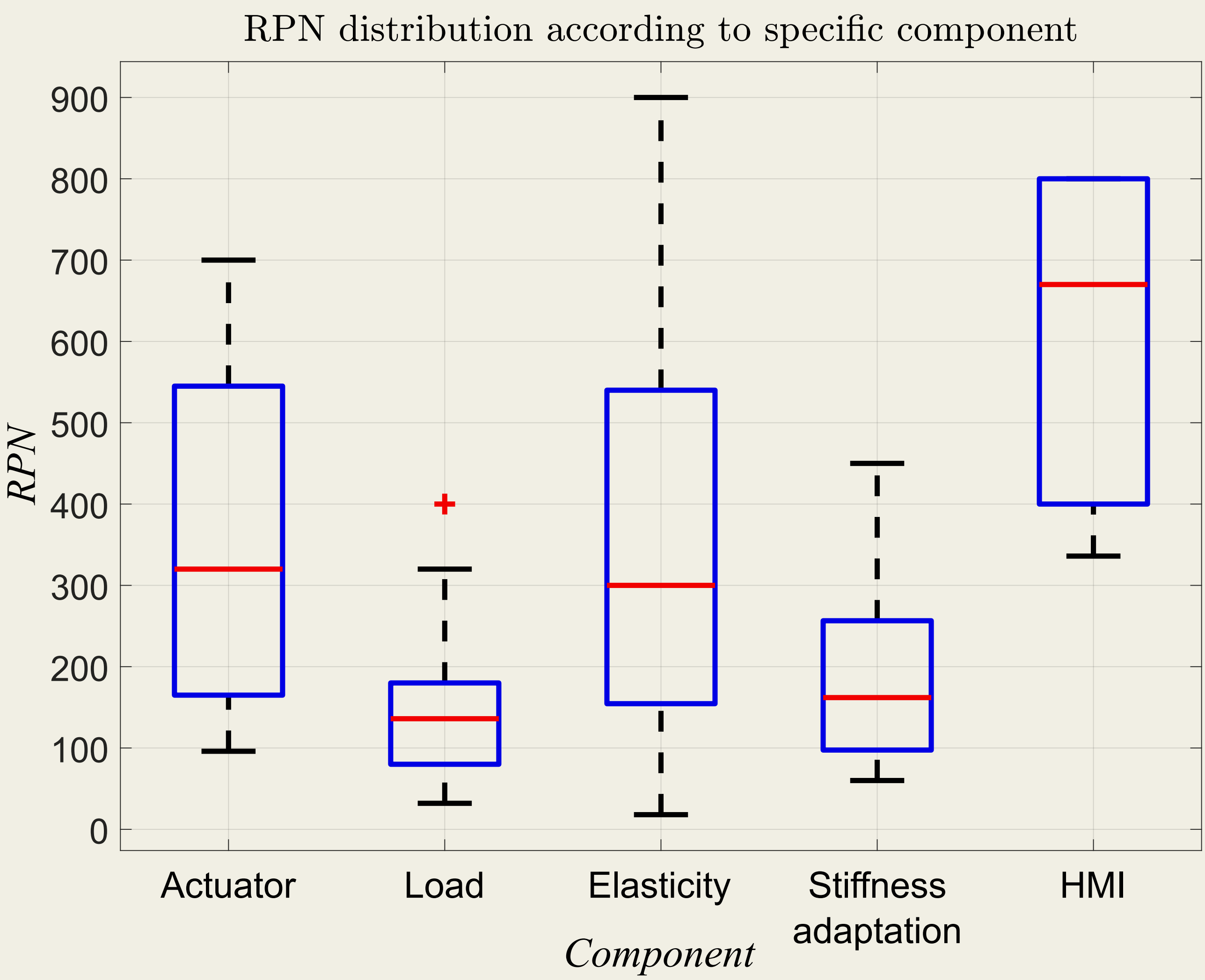


**FIGURE 7:** Box plot of the risk priority numbers of components in the different classes determined by FMEA

RPN values with a median of 670. Additionally, it is noticeable that the elasticity has a very broad range of values (between 18 and 900). This is in accordance with the questionnaire results and due to generally high probability and low detection rate assessment. One reason for this is the prototypic nature of the VTS actuator, which is similarly found in many other elastic actuators developed for research. This outcome of the FMEA highlights the need for an improved knowledge base and the potential relevance of faults in the elastic elements. The encoders are mainly assigned to the actuator, pendulum, and stiffness variation classes and show moderately high RPN values. Overall, actuator and stiffness variation exhibit low RPN ratings since they involve known and industrial proven hardware with low fault probability.

## 3. DISCUSSION AND CONCLUSIONS

This paper extends the analysis of faults in elastically-actuated robots from [14]. The exploration of fault probability and severity is based on an extended data set of 51 expert opinions. The experts' professions and the technical characteristics of the applied actuators are comparable to those in [14]. Due to limited industrial application, most responders have a background in academic research. Additionally, methodological stu-

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dies systematically investigate faults and their impacts considering a VTS actuator as a practical example.

The questionnaire results substantiate those from the previous study and show which components appear to be more prone to faults. Frequent occurrence is reported regarding kinematic components, sensors, and software. It should be noted that elastic elements and actuators receive higher probability ratings which supports the potential relevance concluded by [14]. The results of the FMEA of the VTS actuator confirm the interpretation that elastic elements could be crucial. Beyond supporting the expert survey outcome, the FMEA results indicate that fault affecting human-machine interaction should receive increased attention.

The expert survey yields even higher ratings for overall practical fault relevance than the previous study. This might be due to the increased system complexity and control requirements. It complies with the FMEA results, and highlights the demand to further examine the relevance of faults in elastic actuators as well as fault diagnosis methods and fault-tolerance measures. As the FMEA results basically agree with the questionnaire responses, FMEA appears to be a suitable analysis method and could guide the reduction and/or avoidance of risks in elastically-actuated robots.

Methods for fault analysis and fault diagnosis, and fault-tolerance measures for elastically-actuated robots are promising aspects for future research. To improve the knowledge about faults in such systems, additional questionnaire data would be helpful. The authors invite the readers of this paper to participate in the online study: http://umfrage.rogcampus.de/rogator/TU-Darmstadt/EAF/

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