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Published in:
Wearable Robotics: Challenges and Trends

DOI:
10.1007/978-3-030-01887-0_89

Publication date:
2018

Document Version:
Accepted author manuscript

Citation for published version (APA):
Lopez Garcia, P., Crispel, S., Verstraten, T., Saerens, E., Convens, B., Vanderborght, B., & Lefeber, D. (2018). Failure Mode and Effect Analysis (FMEA)-driven Design of a Planetary Gearbox for Active Wearable Robotics. In *Wearable Robotics: Challenges and Trends* (Vol. 22, pp. 460-464). [978-3-030-01887-0_89] (Biosystems & Biorobotics; Vol. 22). IEEE. https://doi.org/10.1007/978-3-030-01887-0_89

Failure Mode and Effect Analysis (FMEA)-driven Design of a Planetary Gearbox for Active Wearable Robotics

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***Abstract*— Conducting an FMEA for the design of a planetary gear transmission for exoskeletons enables decision making based on the interdependence between design parameters and the device requirements, as well as an early identification of several functional risks. Therefore, the use of FMEAs in the design of wearable robotic devices could contribute to higher design robustness, and ultimately result in a broader acceptance of future active wearable robotic devices.**

I. INTRODUCTION

THE selection of a suitable actuating system for a given application is a common task in machine engineering. In wearable robotics, actuating systems collaborate very closely with the biomechanical actuators of the human body, to improve the performance of the latter. This situation conditions their movement – to match the extraordinary versatile mechanical characteristics of their muscle-based peers – challenging the selection of suitable transmissions.

In this work, we propose to integrate Failure Mode and Effect Analysis (FMEA) in the design process of robotic actuating systems to help manage this complexity. FMEA is a step-by-step approach to identify and categorize all possible failures in a design or manufacturing process [1]. Originally invented around 1950 by the US Army and used in multiple NASA space programs, the automotive industry is reputed for having exploited its full potential to (i) put the user's need at the center of the complete product-design process, (ii) test and improve the accuracy of an initial specification (set of requirements), and (iii) identify interdependencies between design decisions and the requirements of the specification, all these being also valuable elements for wearable robotics [2].

II. FMEA-DRIVEN TRANSMISSION DESIGN

In practice, transmissions are selected from usual technologies used in robotics – Harmonic Drives, planetary gearheads or cycloidal drives among others – to shift the torque-speed characteristic of the actuator and to cope with size and weight restrictions. This choice tends to be strongly dependent on the previous experiences of the engineer.

To systematize this process and understand the potential of using customized instead of standard gearheads, we at the R&MM group conducted a Design-FMEA analysis of a planetary gear transmission for exoskeleton's hip actuation.

A. *Product specifications*

Putting the user's needs at the center of the design is of fundamental importance for the product acceptance and begins with the definition of a robust product specification.

Human actuators are not characterized by a very high efficiency or high specific power characteristics [3], [4], [5]. However, they can provide impressive specific forces well beyond the capabilities of our current actuators, explaining the need for transmissions. And they are enormously versatile to assist the highly dynamic biomechanical actuation, with fast and continuously changing speeds and fast variations of the mechanical impedance (ratio between torque and speed) within a very broad range of values.

Finally, the narrow collaboration between robotic and biological actuators in exoskeletons introduces as well unprecedented mechanical and ergonomic challenges in terms of compliant mechanical interfacing, weight distribution and autonomy.

All these aspects are not yet sufficiently understood and stay in the focus of current research activities [6], [7], [8]. To integrate them in a robust set of requirements, we collected the input of experienced robotic engineers and completed it with further inputs from the literature [5], [8].

B. *System Structure and Functional Net*

The second step of the FMEA consists in defining the assembly structure of the components and subcomponents of the planetary gear transmission.

We then linked each of these components with the specifications through a Functional Net, identifying for each component the internal functions which are responsible for the fulfillment of each of the requirements at complete system (transmission) level, see example in Fig. 1.

C. *Failure Analysis: Consequences and Causes*

Possible *Malfunctions* of each of the derived internal functions of the elements of the planetary gear train, together with their *Consequences* on other internal functions and on

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Elias Saerens and Bryan Convens are SB PhD Fellows at the Research Foundation Flanders – Fonds voor Wetenschappelijk Onderzoek (FWO). This work has been partially funded by the European Commission ERC Starting grant SPEAR (no. 337596).

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The authors would like to express our thanks to APIS Informationstechnologie GmbH (www.apis-iq.com) for supplying the FMEA software used in this research project.

the overall product requirements, were then analyzed with the aid of the *Functional Net* structure.

Additionally, all *Potential Causes* that could result in these malfunctions were identified back to the lowest component level, and included, together with the previously found *Consequences*, in a *Failure Tree* (*Ishikawa*) structure (Fig. 1).

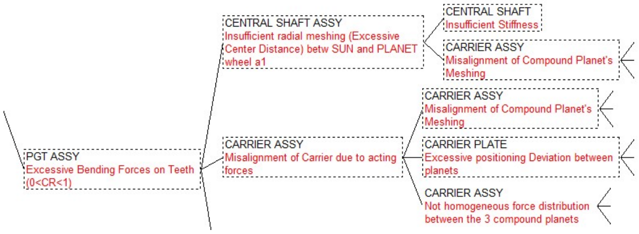
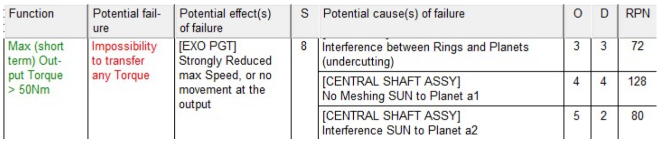


Fig. 1. Extract of the Failure Tree showing part of the Functional Net of the planetary gear, and a portion of the causal-interdependency for the *Malfunction* "meshing Contact Ratio insufficient (0<CR<1)".

D. *Risk Assessment*

Risks are combinations of a certain *Potential Cause*, a *Malfunction* and a *Consequence*. To assess and categorize them, three main criteria are used: *Occurrence (O), Detection (D)* and *Severity (S)*. *Occurrence* refers to the probability of the *Potential Cause* to ultimately occur and in our case, it is linked to the definition of suitable tolerances and safety coefficients. *Detection* refers to the probability of being able to detect the presence of a *Malfunction* during the validation (testing, simulation, etc.). *Severity* is used to assess the criticality of *Consequences* and must be established at transmission overall level (specifications).

For each of these criteria, standardized reference rating tables [1] were used to assess the risks for each malfunction. An additional evaluation criterion (*Risk Priority Number - RPN)* was generated multiplying these three criteria (Fig.2).



Function	Potential failure	Potential effect(s) of failure	S	Potential cause(s) of failure	O	D	RPN
Max (short term) Output Torque > 50Nm	Impossibility to transfer any Torque	[EXO PGT] Strongly Reduced max Speed, or no movement at the output	8	Interference between Rings and Planets (undercutting)	3	3	72
				[CENTRAL SHAFT ASSY] No Meshing SUN to Planet a1	4	4	128
				[CENTRAL SHAFT ASSY] Interference SUN to Planet a2	5	2	80

Fig. 2. Assessments of several risks related to the *Malfunction* "Impossibility to transfer any Torque"

E. *Optimization*

Finally, we reviewed R*isks, Potential Causes* and *Malfunctions* associated with the highest values of *O, D, S* and *RPN,* to assess how design changes, additional testing or simulation could improve the current design performance.

III. RESULTS

Our study allowed us to upgrade our initial design to exploit the potentials resulting from (i) using Ferguson Paradox- planetary gear trains [8] to generate high gear ratios, (ii) adapting the gear teeth shape to the asymmetric torque, back-drivability and backlash demands, and (iii) selecting the diameter to width ratio to optimize ergonomic footprint and minimum gear teeth size to bear the contact surface and bending loading for a certain torque output.

Additionally, it also confirmed the important impact of current limitations of product design in robotics already well identified in previous literature [5], [8], [10]. These limitations result from (i) our limited ability to define a robust specification for actuators due to the complexity of the mechanics and control of the human body, and from (ii) the strongly personalized performance criteria due to the absence of generally agreed validation criteria, adequately integrating inter-user and inter-task variability.

A possible solution to standardize performance evaluation, integrating complex inter-user and inter-task variability and following a similar in approach to the *Benchmarking in Locomotion* initiative [10] and to robot competitions like CYBATHLON, could be based on the use of driving cycles. Driving cycles are successfully applied to homologate vehicles and compare technologies in the automotive industry, where performance depends strongly on the user's driving style and usage conditions [11], and they are a focus of future research in our group.

IV. CONCLUSION

In conclusion, we believe that FMEAs can help make adequate decisions and identify potentials in the design of actuating elements for wearable robotics, while putting the user's needs at the center of the design process.

Their use, combined with the application of usage-adapted driving cycles to validate and compare the performances of different solutions, could contribute to improving the acceptance of future active wearable robotic devices.

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