ICED13
INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

DESIGN FOR FUNCTIONAL REQUIREMENTS ENABLED BY A MECHANISM AND MACHINE ELEMENT TAXONOMY

Szu-Hung LEE, Pingfei JIANG, Peter RN CHILDS
Imperial College London, United Kingdom

ABSTRACT
A process providing an option for engineers and designers to separate the consideration of functional requirements and movement requirements to encourage diverse thinking has been developed and implemented in a graphical interface. In order to assist in consideration of attributes, a database, mechanism and machine element taxonomy (MMET), has been constructed. MMET is composed of the functional attributes, movement attributes, and advantages and disadvantages of machine elements and mechanisms. It provides engineers and designers a wide range of component selection to fulfil design requirements and reliable references to make decisions. Three different interfaces such as hierarchy, functional-oriented and movement-oriented are defined to allow users to explore different options and purposes. This taxonomy also provides comparative information between elements, mechanisms with the same main technical functions. With this information contained in MMET and with the additional aid of a functional analysis diagram (FAD) approach, engineers and designers are able to explore flaws in current designs and deliver alternative solutions by following a proposed creative optimizing process.

Keywords: conceptual design, design process, optimisation, process modelling, functional analysis

Contact:
Szu-Hung Lee
Imperial College London
Mechanical Engineering
London
SW7 2AZ
United Kingdom
s.lee11@ic.ac.uk

1 INTRODUCTION

As a multi-disciplinary subject, engineering design involves not only technological but also human-interactive and organisational issues. Competition to develop products with enriched functions and improved quality in a time and resource efficient manner drives an interest in design process research. Various models for the design process have been developed such as total design, gated design, functional design and the double diamond model (see for example Clarkson and Eckert (2005)). However, no satisfactory model can be applied universally to every circumstance because design is subject to an individual's or organisation's approach, context and culture (e.g. see Bahrami & Dagli, 1993, Pahl et al., 2007), and attempts to decompose the process tends to be imprecise with exceptions. The different types of design process proposed tend to have some level of validity since these processes have typically arisen from a domain specific background (e.g. see French, 1999). Separating design processes into phases can provide useful reference points for designers and management teams to follow.

Mechanical engineering design involves in tasks of designing machines that can deliver force or motion. The functions of these machines are achieved by their interrelated machine elements. (Norton, 2000) A key mission in machine design is to select appropriate components that can deliver required functions but it can take a long time for novice engineers and engineering students to broadly understand different functions and use of machine elements. On the other hand, research on C-K theory suggests that pre-existing knowledge can cause a fixation effect that stops the process of creation. However expansion of knowledge space can help experienced designers to expand their scope of concepts (Hatchuel & Weil, 2003, Agogue, Kazakçi, Weil, & Cassotti, 2011). Studies of the theory of inventive problem solving (TRIZ) also reveals that by exploring alternative options, engineering designers can generate more ideas with improved originality and higher creativity level of innovation (Altshuller, 1984, Altshuller, Shulyak, & Rodman, 1997, Gadd, 2011).

Research on functional representations and functional modelling have focused on analysing functional interrelationships of technical systems while function is thought to be a key instrument of engineering design (Pahl et al., 2007). On the other hand, the research on mechanism design shows that kinematics analysis is another curial concern for designing a system while motion is one of the main functions that a machine should deliver (Buchsbaum & Freudenstein, 1970). Research using Graphical Representation to represent topological structures of mechanisms for kinematic analysis has also been applied to the analysis of linkages and epicyclical gear trains (e.g. Freudenstein, 1971; Shai & Preiss, 1999). This implies the potential usefulness of emphasizing movement analysis in the traditional function-based analysis approach.

The research reported here focuses on the establishment of a component database and an attempt to associate this database with the conceptual design process. While the long-term goal is to develop a conceptual design process for designing new mechanical products that works in association with a database of components with separation of consideration of functions and movements, the first objective of this research is to establish a database, named the mechanism and machine element taxonomy (MMET). Such a database, records functional attributes and merits and drawbacks of different types of machine elements, and intends to provide both novice and experience engineering designers with references for in-depth design consideration and alternative choices of components. It is also aims to expand the knowledge space of engineering designers and allow them to collect elements that fulfil design requirements. In addition, motion transformations of machine elements that could deliver movements are recorded to provide further insights and information for kinematics analysis. As MMET is constructed to support conceptual design, the second objective is to adjust the design process to incorporate MMET at the conceptual design stage. Furthermore, while advantages and disadvantages analysis could be the reference for comparison and design improvement, the feasibility of applying MMET in design optimization process is also considered.

2 MECHANISMS AND MACHINE ELEMENTS TAXONOMY

The Mechanism and machine elements taxonomy (MMET) is a classification containing many commonly used machine elements and mechanisms in the mechanical engineering industry. Examples include springs, gears, bearings, clutches and electric motors. It systematically analyses the technical functional attributes of the different machine elements. This is distinct from the Design Repository developed by the American National Institute of Standards and Technology, which is a top-down structure using a functional modelling referred to as Functional Basis developed by Hirtz et al. to interpret functions and Function Structure and originating from system theory to represent product structure (Bertalanffy, 1969). The idea of MMET is a reversal to the approach used in Design Repository. MMET is a down-top database and no complete product is included in this taxonomy but it contains the smallest units that can be purchased from manufacturers as stock items

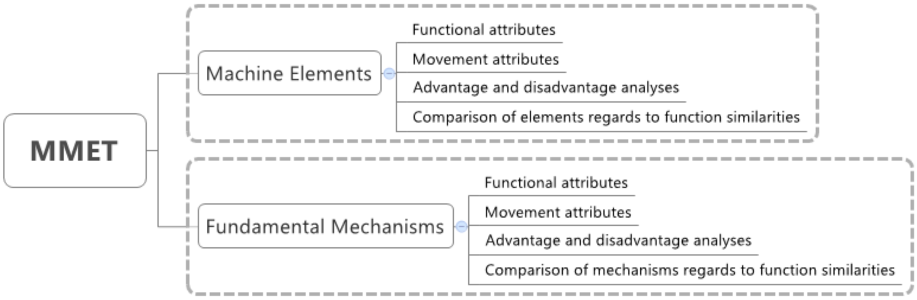

Figure 1 MMET Basic Structure

Figure 1 shows the basic structure of MMET. The aim is to assist engineers and designers understand and select machine elements and mechanisms in a more detail and precision and to enable comparisons. In additional to functional attributes and merits analyses, movement attributes and comparison are also included in MMET to support kinematical consideration and design optimisation. In the current implementation MMET is presented using a mind-mapping tool, designVUE. This was originally developed by Tufts University but modified by Imperial College (Kumar and Schwertner, 2008, Aurisicchio, 2012). It is simple to use, it has a wormhole function that enables the link between different maps.

2.1 MMET database

A few different types of nodes have been used in MMET, as indicated in Figure 2.

Figure 2 Nodes in MMET

2.1.1 Classification

The data collected was classfied into their corresponding category. MMET was divided into two main groups, machine elements and fundamental mechanisms. Under each group there are different types of machine elements and mechanisms shown in a hierarchy form, with the aim of being easy to read and obtain information from. Currently there are fourteen types of machine elements such as belts, gears, springs and thirteen types of fundamental mechanisms such as brakes, clutches, and gear systems in MMET. MMET does not contain all mechanical components, but addresses more commonly used ones, providing a basis for engineers and designer to use.

2.1.2 Functional attributes

Each type of machine elements and mechanisms has their own functions. In order to formalize their technical functional description, a stylized naming approach was used to describe their functional attributes, called functional basis, using a consistent vocabulary of functional verbs and nouns. With the basic functional attributes of these machine elements and mechanisms added into MMET, novice or experienced engineers and designers can use this database in their designs, allowing for experimentation when choosing the type of components. The following figure shows an example of technical functional attributes of one machine element.

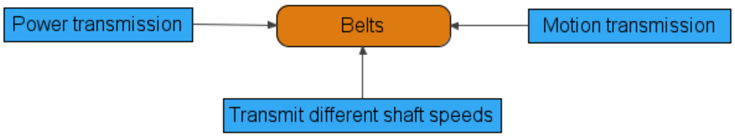

Figure 3 Example of Belt Technical Functional attributes

2.1.3 Movement attributes

The movements of mechanisms and machine elements represent the ability for them to transform motions. For instance, a cam mechanism can transform a rotational input to a reciprocating output. As shown in Figure 4, the input of the cam can be recognised as R_z in accordance to the coordinate system shown in the figure. The roller follower moves on the surface and provides a reciprocating output motion that can be recognised as T_y. Thus the movement attribute of this roller cam mechanism can be recorded as "R_z => T_y."

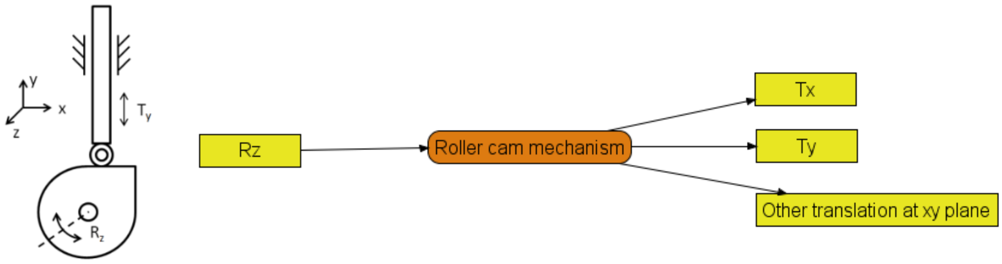

Figure 4 Movement analysis and attributes of a roller cam mechanism

2.1.4 Pros and Cons

When a machine element or mechanism is used in a product, there may be some advantages in choosing it, and it may also cause some problems. Therefore, basic pros and cons of using these machine elements and mechanisms are presented in MMET. Comparison of attributes is an important step frequently undertaken in concept development and detailed design. The advantages and disadvantages of listed components can be analysed to provide designers a reference for their design decisions. Figure 5 shows the analysis of the non-metallic rubbing plain bearing. A "+" represents an advantage while "-" represents a disadvantage. Components under the same category are analysed based on the same subjects in order to be compared.

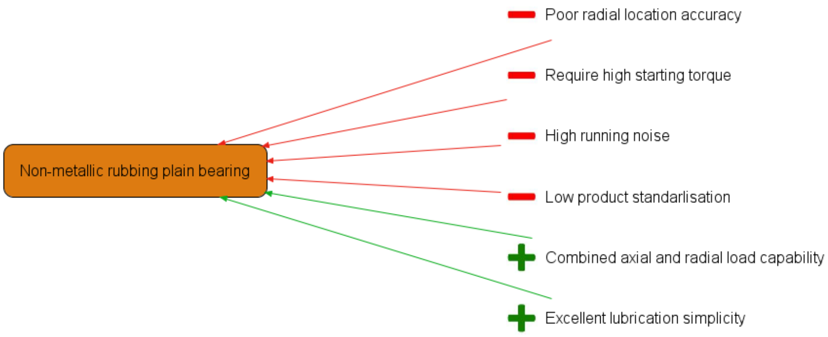

Figure 5 Example of advantage and disadvantage analysis of non-metallic rubbing plain bearing

Table 1 Comparison between hydrostatic bearing and other bearings

Hydrostatic bearing changed to:	Factors					
	Running noise	Starting torque	Radial location	Part standardisation	Combination capability of axial and radial load	Need for lubrication system
Fluid film hydrodynamic	--	--	Worsened	Improved	--	--
Porous metal plain	--	--	--	Improved	Improved	Improved
Non-metallic rubbing plain	Worsened	Worsened	Worsened	Improved	Improved	Improved

2.1.5 Comparisons

The comparison between machine elements and mechanisms provides a different view rather than just focussing on the component itself. The comparisons are only made between elements, mechanisms with same main technical functions, for example, comparison between different types of chains, including roller, leaf, and conveyer. Table 1 shows the comparison of bearings. According to the comparative information contained in the table, risks and advantages of replacing the hydrostatic bearing to other types of bearing can be understood and engineering designers could improve the product with a reliable reference.

2.2 Interface of MMET

MMET has three different inquiring approaches to allow users to search components by component types, functional attributes, and movement attributes.

2.2.1 Component-oriented MMET

The database of MMET is constructed in a hierarchical style and presented in a graphical interface that allows users to search information by clicking icons. This orientation provides an option for engineering designers to compare different machine elements in the same categories. As shown in Figure 6, the bearings recorded in MMET are displayed in a hierarchy structure to allow users to access, gather information, and compare their differences.. Currently the MMET catalogues thirteen types of machine element (Actuator, bush, framework, wire rope, sensor, spring, chain, seal, belt, cam, gear, joint, and shaft) and eighteen types of fundamental mechanisms (Bearing, latch, toggle and trigger, clamp and chuck, gear system, Cardan gears, ratchet, Geneva mechanism, linkages, pulley system, levers, winches, windlass, capstan, brake, and clutch).

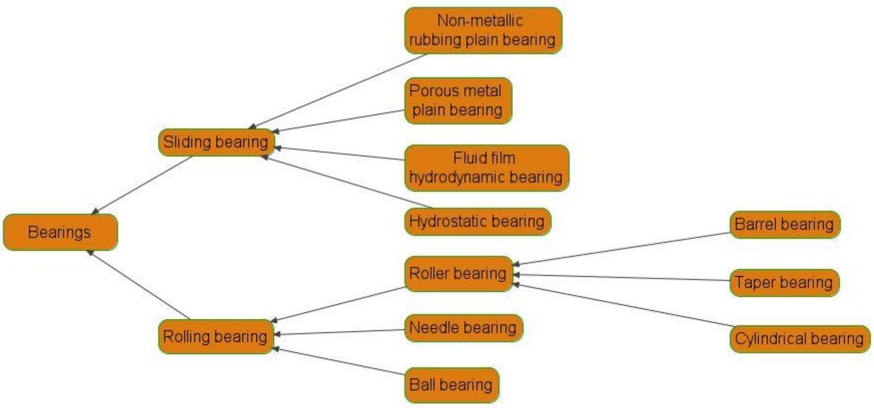

Figure 6 Hierarchy structure

2.2.2 Function-oriented MMET

Based on the functions that these machine elements and mechanism are able to deliver, MMET can be transformed into a Functional-oriented search database system, to aid ease of use for engineers and designers to obtain information. It is able to provide options for machine elements and mechanisms that fulfil desired technical functions. For example, if an energy storage system needs to be designed, Functional-oriented MMET would base this on technical functional requirements, providing options such as springs and batteries. But depending on other design requirements and limitations, the choices may be narrowed down. Functional-oriented MMET can guide engineers to find the most appropriate solutions based on the specific application. The working principle is relatively straightforward. It provides a list of technical functional attributes such as energy storage, supporting static load, transmitting power. Under each technical functional attribute there would be a list of options categorized into groups based their type. Engineers can choose machine elements and mechanisms from the list, note them, and then with other functional requirements, a similar procedure can be applied. After exploring the selection process for machine elements and mechanisms, there should be a number of choices to fulfil the design requirements. Followed by each selection there will be their pros and cons identified and comparisons, helping engineers evaluating the components and provide alternatives for consideration.

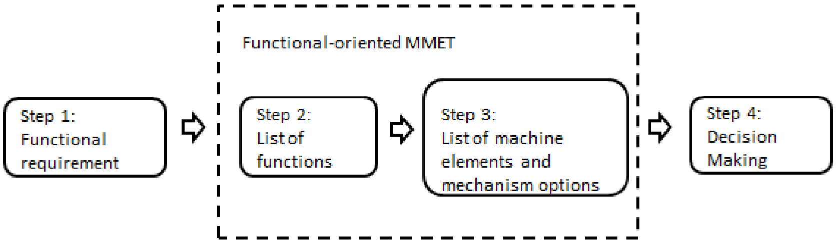

Figure 7 Working instruction of Functional-oriented MMET

2.2.3 Movement-oriented MMET

There are six degrees of freedom (DOF) for all possible movements. Therefore, another option for enhancing the Functional-oriented MMET is to classify the machine elements and mechanisms into movement types, i.e. into six DOFs, Tx, Ty, Tz, Rx, Ry, Rz (T represents translation, R rotations). Some machine elements and mechanisms can accomplish movements more than one DOF in the same time, therefore the list would provide options which fulfil combinations of movements. For convenience, two lists of movements types are provided, input and output. By knowing the movement type, a search can be made to find the appropriate machine elements and mechanisms for the design. The two lists can be cross-referenced by knowing both input and output movements requirements. The working principle of Movement-oriented MMET is same as Functional-oriented, except the cross-referencing feature.

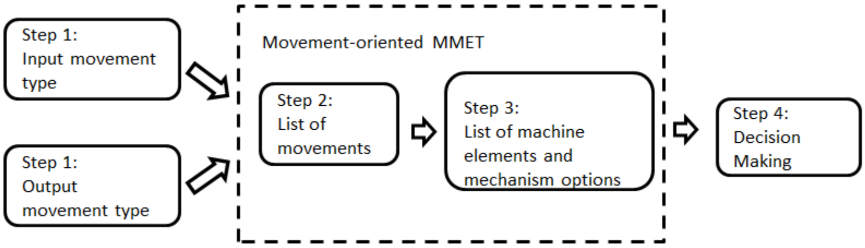

Figure 8 Working instruction of Movement-oriented MMET

3 FUNCTIONAL ANALYSIS DIAGRAM (FAD)

Another important part of this creative design and optimizing process is use of a functional analysis diagram approach. FAD was first disclosed in the patent claimed by Inventive Machine Corporation (Aurisicchio, Bracewell, & Armstrong, 2012, Devoino, Koshevoy, Litvin, & Tsourikov, 2000), a well-known vendor for CAI (computer aided innovation/invention) software. This combines advantages of FAST (SAVE International, 2013), Function structure **(**Pahl et al., 2007) and Concept maps (Novak, 1990), representing functional analysis results using blocks, coloured arrows and labels. The blocks represent artefacts, users and other resources. They are linked by actions in the form of two arrows and a label. Two types of action can be defined as useful and harmful connected by green and red coloured arrows respectively.

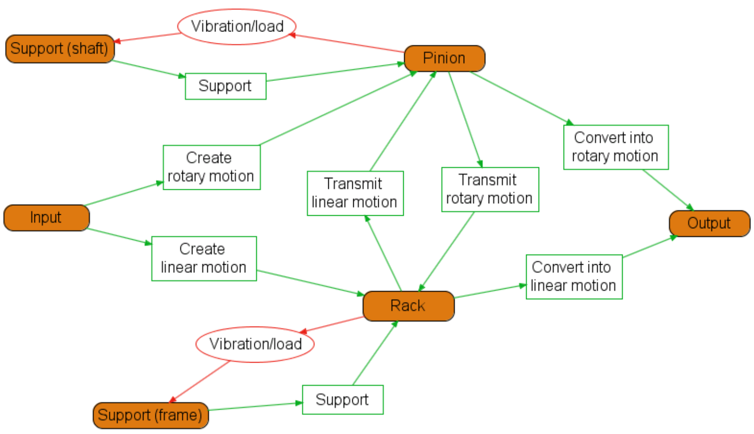

Figure 9 Example FAD for a rack and pinion

Figure 9 shows an FAD example for a rack and pinion. The pinion is mounted on a shaft in this example, so it is supported by the shaft. In the same way, the rack is supported by the housing or frame. Input can be from both rack and pinion, with rotary and linear motion respectively. With one of them being an input, the motion is then transmitted, becoming output but converted into another motion type, i.e. linear to rotary of rotary to linear. When operating, there would be vibration and load created by the moving component to the supporting structure, represented by red arrows since they are normally deemed harmful functions. For complicated products, these can be breakdown into subsystems and then into components. Using FAD can help engineers and designers gain insight and understanding of the product, reveal critical points in the design, identify useful, harmful and useless function (Aurisicchio, 2010). Based on this further development and optimization of the product can be enabled.

4 CREATIVE DESIGN AND OPTIMIZING PROCESS

According to the characteristics of MMET, it can support both new product design and improvement of existing products. Two processes are developed to support these applications, a creative design process and a creative optimizing process.

4.1 Conceptual design process

In most of current design processes, brainstorming and idea generation mainly occurs in the conceptual design stage where some creativity tools can be applied to generate more ideas (e.g. see Thompson, 1999), the more ideas that are generated, the more likely a better solution will be arrived at. However, most of the design processes performs in a serial manner, this may jeopardize intuitive and impulsive designs (Childs, Downie and Katz, 2001). The process developed, incorporating Functional and Movement oriented MMET, and aims to assist users devise a wide range of solutions for the task. The process is focused on use in combination with brainstorming and creative solution finding based on the required movements and functions of the design.

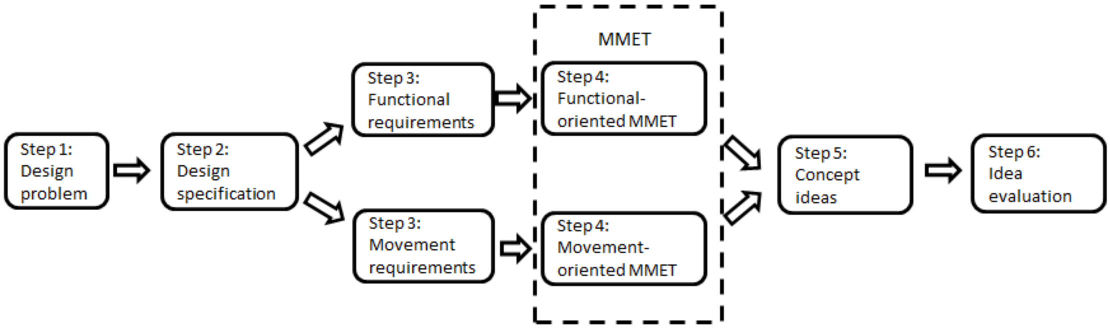

Figure 10 Creative Design Process

From knowledge of the design problem and specification, engineers and designers can determine what types of movements and functions the design should accomplish. They can use the Functional and Movements oriented MMET, and from the list, identify machine elements and mechanisms which can fulfil the required movements and functions according to the suggestions made. If the design problem is simple, it may take a very short time, to find suitable machine elements and mechanisms. With different options for each movement and function required, numerous combinations can be formed by illustrating FADs. Each combination is a potential solution for the problem. For complex designs, the overall task can be separated into sub-systems, with individual function requirements. The database can then applied to devise new sub-system designs. These sub-systems can then be integrated to compose complete solutions. With the assist of MMET, the users could compare these solutions, evaluate trade-offs, and make design decisions.

Similar to the creative problem solving process proposed by Osborn (1953) and Parnes (1967), this process could follow a divergent-convergent development process with divergence for idea generation and convergence for idea evaluation and solution selection by associating MMET. This conceptual design process enables engineers to use creative thinking throughout encouraging a range of possible solutions. For each design concept, there will likely be a range of options given by MMET. Based on experience or prompts suggested by the database, iteration as appropriate and idea evaluation techniques, suitable concepts for the design can be developed.

4.2 Creative optimizing process

Studies have suggested that most new design projects are redesign tasks and thus many new designs have similar previous designs and prior art. These new designs tend to contain attributes that are focussed on compensating for the inadequacies of previous designs (e.g. see Cross, 2000; Ullman, 1992). For such design development tasks, the advantage and disadvantage information contained in MMET can be a useful resource for the design team to refer to when they are considering improving or modifying existing products. Figure 11 shows the flow of the proposed creative optimizing process. This process consists of four steps: technical functional analysis, harmful action analysis, alternative components and designs analysis, and decision-making.

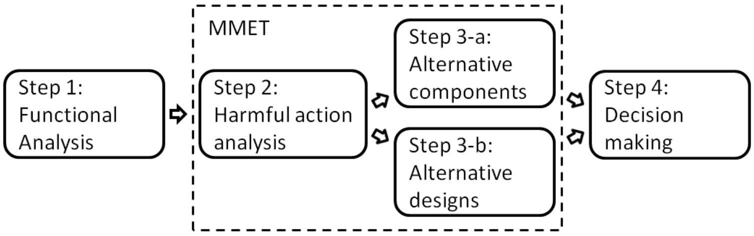

Figure 11 The creative optimizing process

The first step is to perform functional analysis and draw the FAD of the analysed object. Figure 12 demonstrates a partial FAD for the wheel module of a robot designed to work in a desert environment but now allocated to another task in a humid environment. In this case an issue identified is that the internal drum brake at the wheel module may sometimes encounter an issue of not being able to hold the wheel in a steady position.

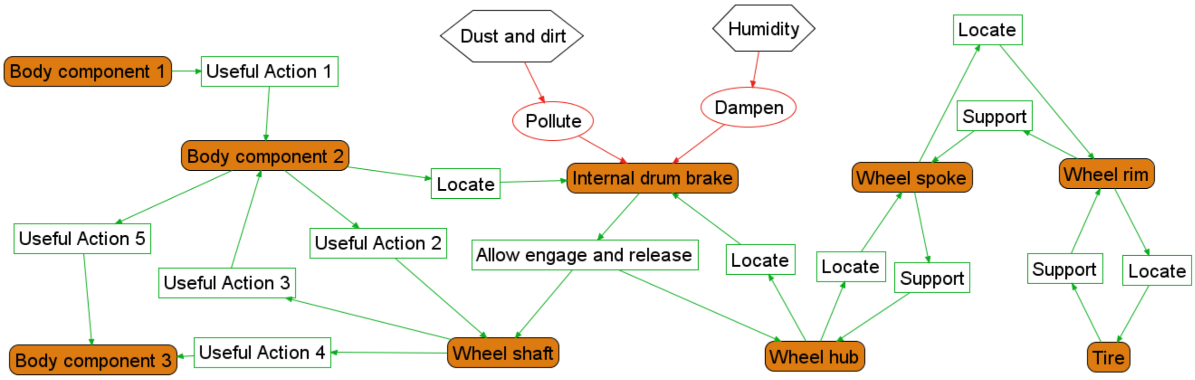

Figure 12 FAD of the wheel module of the sample robot

Table 2 Alternative brake analysis

Internal drum changed to:	Factors				
	Operating temperature	Brake factor	Stability	Humid, wet	Dust and dirt
Band	Worsened	Improved	Worsened	Slightly Improved	Same
External drum	Same	Slightly Worsened	Slightly Improved	Slightly Improved	Same
Disk type	Improved	Worsened	Improved	Significantly Improved	Significantly Worsened
Calliper disk	Significantly Improved	Slightly Worsened	Improved	Significantly Improved	Worsened

The FAD shows the changed environment provides a new harmful action to the brake. The increased humidity may be the root cause since the humidity is higher than in the desert and the performance of the internal drum brake is affected if it is wet. A solution for this situation needs to be developed and both alternative components and design improvements are suggested in the next step. MMET provides a useful reference for component selection. As shown in Table 2, a comparison between internal drum brake and other types of brakes can be searched in MMET. This comparison suggests that both disk brake and calliper-disk brake can improve brake performance in a humid environment. Among these two types of brakes, the brake factor of a disk brake is higher but the dusty environment may be more hazardous to it than to a calliper-disk brake. No perfect brake can be identified in this case that can fulfil the need to work in an environment that is humid and dusty.

Since every type of brake has advantages and disadvantages, it is sensible to consider alternative designs to compensate for the drawbacks of these brakes. The condition in the application is humid and it is not easy to install a humidity blocker or a dehumidifier on the joint. It may however be feasible to design a cover around the brake and seals to prevent it from being contaminated by dust and dirt. The actuation method of the brake should also be considered. Despite the limitation of electromagnetic actuation providing less force than other methods for this application, it is chosen for its small volume and its ability to combine multiple disks to increase brake factor. Thus the design with an electromagnetic multi-disk brake and an additional dust cover is developed as the final improvement of the robot.

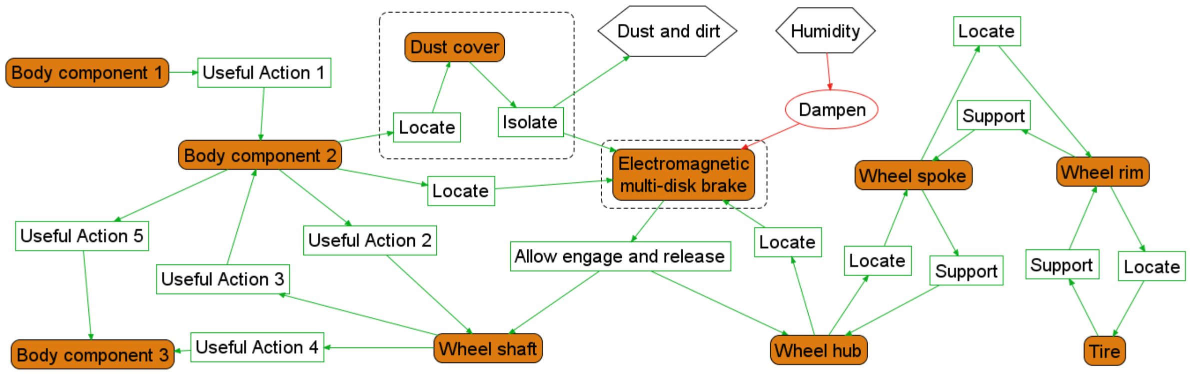

Figure 13 FAD of the final improvement

Table 3 Comparison of brake actuation

Actuation methods	Factors				
	Size	Weight	Maintenance	Structure	Force
Electromagnetic	Small	Lightest	Easy	Simple	Medium
Mechanical	Large	Heaviest	Trouble	Complicated	High
Hydraulic pump	Medium	Medium	Trouble	Complicated	Highest

5 CONCLUSION

This paper has outlined the development of a mechanism and machine element taxonomy and its integration in conceptual design and design optimising process. The purpose of developing MMET is to provide a reliable and useful reference for engineers and designer to search and explore components that can fulfil design requirements. The taxonomy allows users to find components according to their required technical functions and movements and then can support the two proposed design processes. The concept design process focused on divergent thinking using MMET to provide a wide range of solutions based on design specification. The aim of the design optimising process is to help to improve and refine designs. With the assistance of MMET and FAD, flaws in a design can be identified and new ideas to improve the design with alternative components and/or designs can be explored. It is believed that the approach of utilising these processes in association with MMET can not only increase the quantity of feasible ideas generated by both novice and experienced engineers but also provide a reliable reference for them to make decisions. In the future, more case studies will be conducted and the scope of machine elements and mechanisms will be expanded.

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