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ELECTRIC ACTUATOR SELECTION DESIGN AID FOR LOW COST AUTOMATION

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ABSTRACT

The selection of cost effective and efficient actuators is challenging, particularly in Low Cost Automation (LCA). Often decisions are based on the designers' experience or on actuator suppliers' recommendations, potentially leading to the selection of sub-optimum actuators due to lack of applicable experience or the manufacturer's incomplete understanding of the design requirements. This paper describes an electric motor selection procedure for use in the early layout design phase of LCA systems. The procedure aims to enable a designer to identify actuator types that are technically viable options. Its use does not require prior knowledge of the actuators, but only requires inputs based on system/application requirements. Being orientated towards LCA, the selection procedure has been targeted at the application of commonly available electric motors and their associated control technologies.

Keywords: Low Cost Automation (LCA); Selection procedure; Actuator selection.

1. INTRODUCTION

Actuators are common, yet critical, components of automation systems. Their proper selection is therefore a task that design engineers must contend with quite often. In practice, actuator selections are frequently based on the designer's experience or on actuator suppliers' recommendations. The time and risk (during the design, testing and commissioning phases) involved in using an unfamiliar actuator type are so substantial that designers are inclined to avoid it. This may lead to the selection of sub-optimal actuators if the designer does not have applicable experience, or manufacturers have insufficient understanding of the design requirements or give preference to their particular product range when making recommendations.

Low cost automation (LCA) poses particular actuator selection challenges. LCA refers to any technology that creates some degree of automation around the existing equipment, tools, methods and people, using mostly standard components available off the shelf [1]. It generally involves modifying existing or extensively using standard equipment, mechanisms and devices to convert selected manual operations to automatic operations [2]. Usually LCA systems are made in small volumes and, since low cost is a central theme, development cost must also be kept low. This precludes extensive evaluation of alternative actuators. The actuators' costs, on the other hand, are often a substantial part of the system cost, particularly when the whole actuation system and its life cycle are considered (including the purchase, integration, programming and control aspects).

A suitable actuator selection aid can therefore be of significant value when designing LCA systems. Such an aid cannot replace the design engineer, but can help him or her to determine what actuator types are technically viable, while "the final selection of an actuator is left to the system engineer, who is able to balance the relative pros and cons on an objective basis" [3]. The inherent trade-offs involved in actuator selection, e.g. cost vs accuracy, are too complex and industry-dependent to fully address in a general actuator section aid.

The main research questions addressed in the work summarised in this paper are, firstly, whether an actuator selection design aid can be formulated that will be useful in the early design phases of LCA systems and, secondly, what the key aspects of such a design aid should be. The authors found that published selection procedures did not provide satisfactory answers to these questions. The approach subsequently taken was to study the range of commonly available electric motors, their properties and the recommended applications. This information, formulated from an actuator perspective, was then transformed to an application perspective.

The following sections describe and motivate the key aspects of the resulting actuator selection procedure, aimed at the scenario described above and suitable for implementation in software. The procedure presented in this paper focuses primarily on off-the-shelf electric motors, which are arguably the most flexible and commonly used LCA actuators, but subsequent extension to include pneumatic and hydraulic actuators (or even other actuators) is also kept in mind.

2. TERMINOLOGY

Actuator selection can be viewed from different perspectives, which can lead to confusing terminology, as an overview of commercial literature in this area quickly reveals. The following terms were therefore defined as indicated to clarify their use in the work presented here:

Application:

> This is the system into which the actuators will be integrated, which can be a system at the design stage, or an existing system requiring modification. Applications could range from very simple (e.g. a fan) to complex (e.g. a system of robots).

Actuator:

> Actuators are here considered to be devices such as electric motors (with or without power electronic drivers), and pneumatic or hydraulic cylinders or motors (with their associated valves and ancillary equipment). Note that mechanical power transmission components, such as gear boxes, ball screws and belts, are not considered to be part of the actuator, but may be part of the system that interfaces with the actuator.

Actuator properties:

> These are the properties of the actuator from the actuator's perspective. Actuator properties and application requirements may have a one to one correlation, for example a high speed application will require a high speed actuator. As such, actuator properties in many instances share a common name with their corresponding application requirement. However, a high speed actuator can also be considered for an application that only requires a lower speed, thus illustrating the difference between the application and the actuator perspectives.

Drivers:

> A driver can be described as a device which regulates the state of a system by comparing a signal from a sensor located in the system with a predetermined value and adjusting its output to achieve the predetermined output [4]. Several terms have, however, been used to refer to electric motor power electronics, such as controllers, amplifiers, drivers, converters and inverters depending on the actuator of focus. The term "driver" will also include cases where no sensor feedback is provided for in the power electronic unit.

3. SELECTION PROCEDURE

An actuator selection aid basically comprises a user interface, a database of actuators to select from and a set of rules which relate user inputs, in terms of selection criteria, to the capabilities of each actuator in the database. The user interface is not considered in this paper, but the rules must be suitable for implementing in the user interface. Section 3 considers the selection procedure as a whole, while Sections 4 and 5 consider the selection criteria and the rules that relate selection criteria to actuator capabilities. Section 6 considers the database itself.

3.1. Target design phase

Since actuators are often some of the most expensive components in an automated system (in terms of purchase, system integration, maintenance and operating costs) and the remainder of the design is strongly influenced by the actuator selection, the selection should ideally be done early in the layout design phase. The resulting objectives for the selection aid proposed here are therefore:

- It must be quick to use, since many design iterations occur in the early phases.
- It may only require inputs from the user that are typically available early in the layout design phase, and it should specifically not require knowledge about the actuator properties, but only of the application requirements.
- It must be useful even when the available information is incomplete, as is typical of the early design phases.

- It must help a designer to assess whether the investment in time and development risk to use a new type of actuator, is worth while.

The actuator selection procedure has to strike a balance between two extremes: on the one hand, it should give information that is as precise as possible to simplify design decisions, but on the other hand it should not require too highly detailed inputs, so that it can be applied earlier in the design process when design details may not have been finalised. In the procedure presented here, the authors have given higher priority to the aid being used earlier in the design process, rather than giving more precise results, since the impact of early design decisions on the final cost are usually greater.

To achieve the objectives just mentioned, the selection process starts with a large design space containing all the actuators in a database, and reduces this space by eliciting application requirements from the user. As the user specifies more and more information, the unviable actuators are identified by comparing application requirements and actuator properties, and are removed from the design space. Eventually, the user is presented with a list of all the "surviving" actuators, from which he/she can make a final selection.

The subtractive approach (starting with all actuators in the database and removing unviable ones) allows the user freedom to enter as many or as few application requirements as is available at that stage of the design process. It is further not feasible for a general procedure to aim to provide a single "best" option, since the general procedure cannot cater for all the peculiarities of a particular application. These peculiarities remain the responsibility of the designer in the procedure presented here. After entering as much information as he/she prefers, the designer can further investigate the list of viable actuators and obtain more detailed or specific information from the vendors that will help him/her to make a final decision.

Actuator cost is always a consideration in the selection process, but the selection cannot be done purely on the basis of actuator purchase cost. Factors that can lead to a preference for a more expensive actuator include the development cost, commonality with other actuators, operating cost, maintenance cost, provision for future upgrading, and cost savings or simplifications in the remainder of the system. When presented with a list of viable actuators and their relative costs, the designer will best be able to judge the advantages and disadvantages of the various options. This type of decision should ideally be made early in the layout design phase to allow the various trade-offs to be made.

3.2. Selection procedure methodology

The selection procedure combines the top-down and bottom-up approaches [5]. The top-down approach involves starting with considering the application, investigating its requirements, progressing towards the actuator properties, and eventually selecting the actuators. The bottom-up approach involves starting with a set of known actuator properties and investigating how they can be combined to achieve the required application. To allow the selection procedure presented here to be used by designers that are not familiar with the actuators' properties, the procedure must follow a top-down approach in the way it interacts with the user (item 3 in Figure 1). Internally, the selection procedure must, however, use a bottom-up approach to provide a traceable path linking the various actuators in the database, expressed in terms of their actuator properties (as derived from their designs, item 1 in Figure 1), to the related application requirements (item 2 in Figure 1). These connections provide an apparent link between the proffered actuator solutions (item 4 in Figure 1) and the application.

Note that the process illustrated in Figure 1 is independent of specific applications. Links 1, 2 and 3 are expressed in terms of the selection procedure rules, which relate the application requirements (expressed in terms of the selection criteria) to actuator properties. The rules are described in detail in Section 5.

4. SELECTION CRITERIA

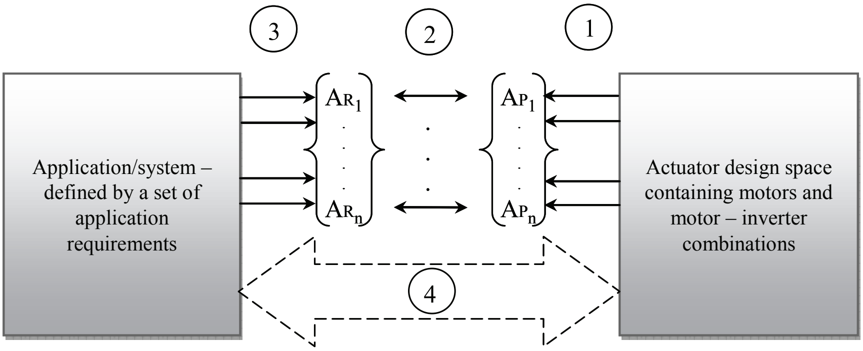
4.1. Overview

Since there is an almost limitless number of actuator designs that can be employed in a given system using any number of mechanisms [6], and there is a large variety of systems in which actuators are implemented, formulating a set of selection criteria is particularly challenging. A few formulations of selection criteria have been reported in literature. Zupan, et al. [7] defined several criteria as normalised actuator attributes for the selection and description of actuators, with a focus on mainly linear actuators. The use of normalised criteria gives a somewhat generic description of actuators.

Anjanappa, et al. [8] defined performance parameters as selection criteria for actuators. Andrew, et al. [9] defined actuation scenarios (specific combinations of application requirements), but these scenarios did not adequately cover the LCA set under study.

For the design aid proposed here, the authors found that the key requirements for the selection criteria are:

- They have to express actuation requirements in terms that can be related by the rules to actuator properties.
- They have to be kept as generic as possible, and ideally be applicable to all actuators types.
- They must enable determining an actuator's applicability to a specific system.
- They must allow implementation in a user friendly design tool.



Application requirements (AR$_1$ – AR$_n$)
Actuator properties (AP$_1$ – AP$_n$)

1 – Correlation of actuator designs to actuator properties (AP$_1$, …, AP$_n$)
2 – Correlation of actuator properties (AP$_1$, …, AP$_n$) to application requirements (AR$_1$, …, AR$_n$)
3 – Correlation of user defined application to application requirements (AR$_1$, …, AR$_n$)
4 – Apparent link between user defined application and actuator design space

Figure 1. Selection procedure formulation process

4.2. Criteria definition

This section presents the selection criteria chosen for the design aid.

Technical and commercial literature sometimes uses different terms for the same property, or even the same word for different properties. Making affected terms distinct and unambiguous is necessary to also ensure clarity, consistency and adaptability of the procedure to a wide range of actuator types with similar properties. The terms used for the criteria are therefore briefly described below.

Each criterion is expressed as an "application requirement", which can be decided by the design engineer even if he/she does not have previous experience with or knowledge of the actuator properties. Although some of the criteria, such as starting current, relate primarily to electric motors, most are applicable to all actuators generally used in LCA.

4.2.1. Range of motion

An application's range of motion requirement can be classified as one of the following:

- Rotary with an infinite displacement capability
- Rotary with a finite angular displacement/stroke
- Linear with a finite displacement/stroke

Mechanical power transmission devices or mechanisms (e.g. toothed belts, ball screws, and slider-crank mechanisms) can be used to convert one type of range of motion into another, but since these devices are very diverse, they are not considered to be part of the actuator in the present procedure.

4.2.2. Available power supply

This criterion in a broad sense specifies the nature of the power available for use by actuators. Even though power could be supplied in one form and converted to another form as required by the actuator, this conversion requires additional equipment and cost, which influences the selection. The designer has to trade off the advantages and disadvantages of such a conversion.

For electric motors, power could be supplied as AC single-phase, AC three-phase or DC (e.g. battery power), and has a significant influence on the selection. Hydraulic power packs are usually considered to be part of the actuation sub-system. Their power supplies are typically either electric power or internal combustion engines. Some LCA environments have installed compressed air systems, which are the preferred power supply of pneumatic actuation systems, but alternatively compressor sub-systems operated from electric power supplies can be added to the actuation sub-systems.

4.2.3. Speed and torque/force range

Since actuators in automation typically impart movement, rotational/linear speed and torque/force are fundamental requirements. The range, or specific values, of the speeds and torques/forces required by the application (note that both the upper and lower limits may be important) determine whether a particular actuator is viable.

In electric motor selection, determining the system speed and torque/force requirements form the basis of most selection calculations and speed-torque/load characteristic curves. The process of determining these values for applicable motors is often referred to as “electric motor matching”.

Lower limits in speed can be important since some electric motor and driver combinations will only give smooth operation down to a certain minimum speed. If the application requires lower speeds, the use of a speed reduction device, such as a gearbox or a belt and pulleys, may be used to bring that speed within the operating range of the motor. Since there is an enormous range of speed reduction devices, they are not considered to be part of the actuator in the selection procedure and the designer will have to consider the use of such devices before formulating the application requirements.

4.2.4. Load characteristics, start duty and duty cycle

Each actuator can only sustain certain load characteristics, which makes it an important selection criterion. Electric actuators are usually more sensitive to load characteristics than hydraulic and pneumatic actuators. Typical load characteristics for electric actuator applications are:

- Constant torque, variable speed loads
- Variable torque, variable speed loads
- Constant power loads
- Constant power, constant torque loads
- High starting/breakaway torque followed by constant torque

Certain electric motor designs are inherently better suited to some of the above load characteristics than others. Other motors may be adapted to sustain these load characteristics by using drivers.

Start duty may be described as a combination of frequency of starts as well as the loading conditions at start up. Duty cycle could be of two main types, i.e. continuous or intermittent operation. For electric motors several other types, such as repetitive duty, have been defined [4]. Electric actuators may be better suited to either continuous or intermittent duty cycles depending on their design, type or technology. In hydraulic actuation sub-systems, the viability of using accumulators is strongly influenced by the duty cycle, since smaller hydraulic power packs with accumulators will be advantageous in some intermittent duty applications.

4.2.5. Controllability

Automation applications will require some level of control for speed, position or torque. Applications may require control with respect to these parameters in different combinations and to different accuracies. The choice between open loop and closed loop control determines to a large extent the degree of precision. In this context, "closed loop control" refers to a situation where the actuation sub-system has its own closed loop control, whereas "open loop control" may include situations where there is no feedback or where the control feedback is external to the actuation sub-system (e.g. through a main control system). Overshoot limitation may be an important consideration in some applications and is considered to be part of the controllability criterion. It is important to note that in the case of electric motors, controllability is highly influenced by the use of drivers and therefore determines the selected motor as well as whether a driver is required with that motor.

4.2.6. Speed variation

Speed variation is particularly relevant for open loop control situations and speed variation is here considered to be "constant", "adjustable" or "variable". The latter two terms, as used here, are defined as follows: An "adjustable speed" actuator has the property that its speed can be manipulated by the user when necessary, while a "variable speed" actuator is characterized by usually small speed variations about a nominal value (e.g. an electric motor's mean synchronous speed) due to changes in loading conditions.

Although this criterion is relevant for all actuators, it has particular significance for electric motors since the design of an electric motor could make it inherently suitable for constant speed, variable speed or adjustable speed applications. An electric motor could also be a combination of variable and adjustable speed or constant and adjustable speed, due to its inherent properties or properties acquired by using drivers.

4.2.7. Directional requirements

Directional requirements can be either unidirectional or bidirectional and can refer to the direction of the motion or the torque/force. For example, a fan with blade rotation in only one direction requires a unidirectional motion while a conveyor that moves back and forth requires bidirectional motion or reversibility. Some applications may require the actuator to act as a brake during some stages of operation, and then the torque/force requirement is bidirectional. Drivers are capable of altering the directional operation modes of electric motors.

4.2.8 Noise and thermal emission

An application may impose limits on the allowable noise and thermal emissions of an actuator. Applications in which these are of concern, usually require that sound and heat generation are kept to a minimum. Although these criteria are relevant for all actuators, they have particular significance for electric motors since a motor's design can make it inherently more or less suitable. For example, the brushless DC motor produces low thermal emissions, which makes it suitable for applications in which temperature is a constraint. Similarly the ability of an actuator to function as silently as possible could be used as a possible criterion for its selection, as in the case of DC servo motors.

4.2.9. Environmental considerations

This criterion prescribes the working condition imposed on the actuator. Some actuators are able to function normally in harsh/corrosive environments by virtue of their design or enclosures, others by virtue of their technology, operating principle or size on the micro and nano-scale.

For electric motors, enclosures are designed which are specifically suited to environments which are corrosive, dusty, explosive, fluid dripping, splashing, etc. By virtue of its design the DC brushless motor is capable of functioning in a vacuum, making it suitable for aerospace applications. Some actuator technologies on the micro and nano-scale, by virtue of their size, are better suited to operation in a wide variety of environmental conditions.

4.2.10. Starting current

Starting current is another criterion with greater relevance to electric motors than for other actuator types. Further, this criterion is only relevant for motors without drivers, since drivers may be used to change the starting characteristics of the different motor designs.

4.2.11. Purchase cost

Actuators are often some of the more expensive sub-systems in an LCA system and cost is therefore an important selection criterion. As pointed out in section 3, other costs such as system development, integration, maintenance and operating costs are also relevant in actuator selection, but their relationship with the actuator properties is less direct and therefore best left to the designer to judge.

For example, maintenance and operating costs are strongly influenced by the maintenance procedures applied and the duty cycles.

The purchase cost of an actuation sub-system is usually strongly influenced by the required accuracy and control. The designer must therefore strike a balance between the accuracy/control required and the cost of achieving such accuracies or control.

The purchase cost of a particular actuator is a property that varies in time and from one supplier to supplier another. The selection procedure therefore cannot be based on exact purchase costs, but at best a cost index suitable for comparative costs.

4.2.12. Size and weight

Size and/or weight can be very important criteria in actuator selection and significantly limit the actuator options. Size in many cases has a direct relationship with weight, as smaller actuators are typically lighter. This is of great importance in aerospace or small/miniature robotics applications where there are rigid weight and/or size constraints imposed by the functionality of the application or its operating environment.

4.3. Selection criteria priority

The importance of a particular selection criterion is highly dependent on the application and, therefore, the order in which the user has to make selections should therefore ideally not be prescribed. The selection criteria defined above generally include the properties that describe performance, which is always important. Weight and size are sometimes critical and are treated as important constraints. Reliability and maintainability are important, particularly in large complex machinery operating away from maintenance facilities. The most important issue, according to Vaidya [10], is the cost of the actuator that provides all the required performance characteristics.

In the selection procedure described in Section 3, a subtractive approach was chosen. As the user chooses options or values for the selection criteria, the number of feasible actuators will gradually reduce. The user may, at some point, make selections that are mutually exclusive, resulting in the disqualification of all the actuators in the database. It would therefore be convenient to apply selection criteria with a high priority earlier and those with a low priority later, so that the user can "back track" if no feasible actuators remain.

When a criterion only makes sense when a particular option for another criterion has been selected, the order in which the criteria are considered becomes important. However, since preference is given in the procedure to minimise restrictions on the order in which the user applies the criteria, the selection procedure is divided into only three sequential phases, illustrated in Figure 2. The user must complete a phase before moving on to the next one and, in a given phase, the user interface will inform the user when options become unavailable due to previous selections (e.g. by "greying out" the unavailable options).

The first phase in Figure 2 entails only the selection of "range of motion" since that would typically determine the nature of many of the selection criteria (linear or rotary type selection criteria) available to the user in the second phase. The second phase considers most of the other application requirements such as speed, torque, etc. Finally, the third phase considers selection criteria, such as cost and size, which usually do not have absolute limits.

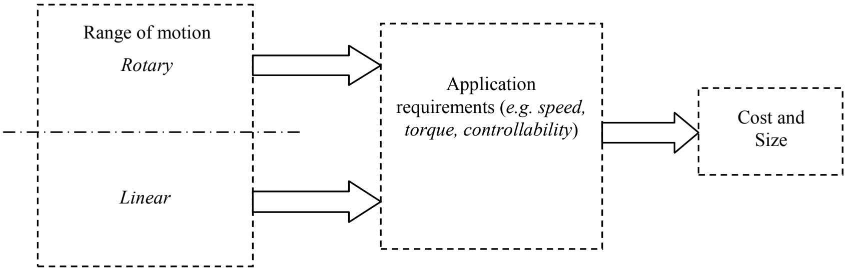


Figure 2. Criteria selection phases

5. SELECTION PROCEDURE RULES

The selection rules, used to decide whether a particular actuator's properties meet the application requirements, are the core of the selection procedure (item 2 in Figure 1). The rules discussed in this section are applied in the second phase in Figure 2. The rules for the first phase are obvious, while the third phase's rules are too complex to formulate explicitly for all applications. To complete the third phase, the user is presented with a list of actuators that meet the criteria imposed in the first two phases. The list includes each option's values for the criteria assessed in the third phase and the user has to intuitively weigh these criteria against each other and the relevant application requirements.

Tables 1 to 9 summarise the rules for the second phase in Figure 2. Application requirements in Table 1 are simultaneously also actuator properties. The associated rules are therefore to eliminate all actuators that do not have the required properties. The default would be for the user to make no choice, thus not eliminating any actuator from the design space. The remaining application requirements, listed in Tables 2 to 9, do not have one to one correspondences with actuator properties. The speed and torque/force rules in Table 2 are simple "less than" or "greater than" tests. In the remaining tables, an “X” indicates that actuators with the particular property (given in the column heading) do not satisfy the corresponding application requirement (given in the row heading). Tables 7, 8 and 9 focus on control related rules. The thresholds in these tables were taken from SEW Eurodrive [11] and experimentally validated by Egbuna [12].

Table 1 Selection criteria directly associated with application requirements

Selection criterion	Application requirement
Available power supply	Unknown/AC 3-phase/AC 1-phase/DC
Control type	Unknown/Closed loop/Open loop
Torque control	Torque control – Yes/No
Directional requirements	Unidirectional/Bidirectional
Quiet running	Quiet running – Yes/No
Low temperature emissions	Temperature sensitive – Yes/No
Environmental considerations	Normal/Vacuum/Corrosive or harsh

Table 2 Speed and torque/force ranges

Application requirement	Rule
Speed	If a target speed has been specified, eliminate an actuator if its minimum speed is greater than the target, or its maximum speed is less than the target
Torque/force	If a target torque/force has been specified, eliminate an actuator if its minimum torque/force is greater than the target, or its maximum torque/force is less than the target

Table 3 Speed variation

Application requirement	**Properties of eliminated actuators**		
	Adjustable speed	Variable speed	Constant speed
Adjustable speed		X	X
Variable speed			X
Constant	X	X	

Table 4 Starting current requirement

Application requirement	**Properties of eliminated actuators**	
	Low starting current	High starting current
Approximately less than or equal to operating or rated full load current allowed		X
Greater than operating or rated full load current allowed	X	

Table 5 Start duty requirement

Application requirement	**Properties of eliminated actuators**		
	Light start duty	Mild start duty	Severe start duty
Less than nominal loads with infrequent starting			
Nominal loads with infrequent starting	X		
Greater than nominal loads with frequent starting	X	X	

Table 6 Application load characteristics

Application requirement	**Properties of eliminated actuators**						
	Constant torque and variable speed	Variable torque and variable speed	Constant power	Constant power and constant torque	High start/breakaway torque followed by constant torque	No torque control	Low start torque
Constant torque and variable speed		X	X		X		
Variable torque and variable speed	X		X	X	X		
Constant power	X	X		X		X	
Constant power and constant torque		X			X	X	
High-start or breakaway torque followed constant torque	X	X		X		X	X

Table 7 Position control requirement

Application requirement	Properties of eliminated actuators			
	Position control > 360°	Position accuracy < ±360°	Position accuracy < ±5° to ±45°	Position accuracy < ±1°
Position control > 360° or no control				
Position accuracy < ±360°	X			
Position accuracy < ±5° to ±45°	X	X		
Position accuracy < ±1°	X	X	X	

Table 8 Speed control requirement

Application requirement	Properties of eliminated actuators			
	No speed control	Speed deviation 0.20% to 1.8%	Speed deviation 0.17% to 1.5%	Speed deviation 0.03% to 1.0%
No speed control				
Speed deviation 0.20% to 1.8%	X			
Speed deviation 0.17% to 1.5%	X	X		
Speed deviation 0.03% to 1.0%	X	X	X	

Table 9 Overshoot restrictions

Application requirement	Properties of eliminated actuators			
	Overshoot > 360°	Overshoot < ±360°	Overshoot < (±5° to ±45°)	Overshoot < ±1°
Overshoot > 360°/No control				
Overshoot < ±360°	X			
Overshoot < (±5° to ±45°)	X	X		
Overshoot < ±1°	X	X	X	

6. ACTUATOR DATABASE

The information contained in the database of the selection aid must meet the following requirements:

- The level of detail of the information must facilitate decisions in the early layout design phases.
- The database must be able to contain all actuators that are commonly used in LCA applications.
- The information in the database must be maintainable and expandable.

For the selection procedure presented here, the database must contain all the common LCA actuators and each one's properties in a format that allows the rules to be applied. For the selection of electric motors, properties peculiar to specific designs are mainly found in textbooks and academic literature. Specific values and data concerning motor designs such as rated speed, torque and dimensions are readily available from motor catalogues. The purchase cost of an actuators can usually only be obtained through requests to suppliers.

Information from the various sources have to be integrated to form the actuator design space illustrated in Figure 1. Several problems arise in trying to achieve the integration. These problems influence the structure and content of the actuator design space.

Firstly, making the design space specific with regards to manufacturer models is difficult as no one company provides all the actuators considered to be LCA alternatives. Indicating models also would make the space unmanageable with excessive drive alternatives of similar performance and properties (redundancy). To overcome this problem, the actuators are classified according to their design, and independent of manufacturer models. Secondly, most electric motor manufacturers tend to use names indicative of motor enclosures or some other motor characteristic specific to the manufacturer (e.g. asynchronous, synchronous, totally enclosed DC, geared, watertight, etc.).

Some of the more general motors most readily available and in use everywhere [13], are squirrel cage motors, synchronous motors, wound rotor induction motors, as well as a few DC brush and brushless motors. The eventual decision on what motors fully describe the choice available to the engineer is dependent on a number of factors. An important factor considered here is the off the shelf availability of the motor, which is more limiting in a small developing country (like South Africa where the research presented here was conducted) than in larger first world countries.

The following is a list of motors which is best representative in type and design of the LCA motor set in South Africa: AC induction motors (asynchronous), AC synchronous motors, stepper motors, servomotors, brushless DC motors, and brushed DC motors. Squirrel cage motors (asynchronous AC induction motors) are the least expensive requiring very little control equipment or power electronics, while the wound rotor is more expensive requiring additional secondary control, and synchronous motors are the most expensive requiring DC excitation as well as special synchronizing control. As size decreases and power requirements diminish (e.g. battery powered applications), DC motors become attractive as they become more economical than their AC counterparts [3]. For very large applications, AC motors become the economical choice as large DC motors with the required properties tend to be very expensive and uneconomical. DC drivers are however generally cheap and not as complex as those required for AC motors.

A very important aspect of electric motor selection is the use of drivers since the properties of a motor with a driver can differ significantly from that of the motor alone. A similar trend can be seen in pneumatic and hydraulic actuators where the reduction in cost of power electronics and electronic controllers has lead to significant improvements in controllability. Only drivers available off the shelf were included in the database, in accordance with the LCA approach. To handle the myriad of drivers available off the shelf, operating principles and functional capability were used as a means of classification for drivers accompanying actuators: voltage flux vector control (VFC) and current controlled flux vector control (CFC) inverters accompany AC motors, regenerative and non-regenerative drivers accompany DC motors, while wave, two phase and half step drivers accompany stepper motors.

7. CONCLUSION

This paper presents the formulation of a generally applicable and easy to use actuator selection procedure oriented towards LCA, with primary focus on electric motors with and without drivers. The formulation of rules used in the procedure to relate actuator properties to application requirements is discussed. The procedure enables a user, knowing only the application's requirements, to determine all the commonly available actuator types that could be considered as technically viable solutions for a particular application.

In conclusion, this selection procedure provides the ability to make cost effective, unbiased and experience independent actuator selection decisions for Low Cost Automation. The described selection procedure was utilised in the development of a prototype software selection aid [12].

The hypothesis that the proposed selection procedure is a useful design aid in the early phases of LCA will be tested in further research through case studies and eliciting experts' evaluations.

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