26 Toward Broader Education in Control System Design for Mechanical Engineers: Actuation System Selection and Controller Co-design

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Abstract. Control system design education for mechanical engineers, in its current form, focuses primarily on control algorithm design. We argue here that control system design is performed best when it is broadened to include requirements development and actuation system design, to be performed jointly with design of the control algorithm. We review practices in specifying control system performance and capabilities of actuation technologies for control applications. An existing unifying framework for representing actuation system capabilities and their selection for applications of interest is presented and assessed. Developments needed for an improved methodology for actuation system selection are enumerated. First, actuator comparison must be extended to include system-level characterization of performance. Second, mechanical actuation applications should be classified in more generic terms and application requirements framed accordingly. Third, compilation of performance characteristics for actuators and actuation systems need to be more comprehensive and better linked to underlying technological limitations.

1 Motivation and Introduction

Control system design education for mechanical engineers, as currently implemented, focuses primarily on control algorithm design and underemphasizes the selection and design of mechanical actuation systems, as well as the formulation and significance of performance requirements for different

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applications. We focus here on applications requiring high performance and closed loop control because of the unique associated knowledge base. In typical undergraduate controls curricula, students are ‘given’ the mechanical actuation system and load, and system performance requirements ostensibly suited to the application, and the bulk of their efforts is directed at modeling and analysis of the given physical system, and feedback control algorithm design to best meet the performance specifications. Issues related to the selection of the actuation system, both the technology of actuation and the sizing of the actuation system components, are essentially underemphasized and, in most cases, avoided. In graduate controls courses, as a rule, the emphasis on control algorithm design is even greater, since the control applications studied are chosen intentionally to be more demanding in terms of performance in order to illustrate the need for more sophisticated control algorithms. As in undergraduate courses, the selection/design of the mechanical actuation system is usually not considered. Actuators and actuator selection are usually considered in classes on mechatronics, but the emphasis in these courses is on familiarizing students with multiple actuation technologies and quantitative understanding of the static and dynamic performance of these technologies. Issues such as rational procedures for selection of actuation technologies based on desired performance specifications are rarely addressed, and considerable weight is placed on conventional practice in performing the task. The more narrowly defined task of sizing actuation system components is usually structured so as to meet basic performance requirements such as maximum loads, accelerations or velocities appropriate for the application, rather than a more complete set of performance requirements characterizing an acceptable level of dynamic performance.

In the current educational context of interest then, to take an example, if we are considering the feedback control of slide position on a machine tool, *determination of* control system *performance requirements* based on machine tool use, and *selection* of the appropriate actuation technology, e.g. hydraulic power versus electrical power, based on the performance requirements, would be rarely addressed by the student. Instead, the actuator for the application would be specified, usually reflecting prevalent engineering practice, and would be considered as part of the plant being controlled. The emphasis in most cases would then be on modeling and analysis of the given plant’s dynamic response, and synthesis of the appropriate control algorithm to achieve the specified closed loop performance. In mechatronics courses, selection of the actuation technology is considered as a task performed prior to and largely independently of the rest of the control system design. Sizing of the actuator itself based on performance specifications related to needed force/torque/power/motion is relatively straightforward once the actuator type has been chosen, and is usually treated adequately.

The focus of control design being on control algorithm design, and the perspective on actuator selection as a function undertaken prior to controller design, reflects current industrial practice where actuation system selection is viewed as part of the mechanical design of the system. The role of the control system designer is seen as beginning after mechanical design decisions have been made, and the task of the control system designer is seen as getting the best performance from the chosen design hardware, rather than helping select the actuation type and hardware as well to best match the desired system performance. The current emphasis on control algorithm design reflects appropriately the knowledge-intensive nature of the control algorithm design task, the largely manual performance of that task in current practice, and hence the need for practitioner and student competence in this skill.

The central premise of this paper is that control system design is performed best when specification of the desired performance of the control system, selection of the actuation technology and sizing of the actuator, and design of the control algorithm are carried out jointly, with full awareness of the interactions between different aspects of the overall design. Such an approach offers potentially greater returns in terms of achievable system performance, and the corresponding skill would be valued as a higher-level skill by employers of controls engineers. We argue here that education in the broader control system design function, involving performance requirements development for applications and mechanical actuation technology and actuator selection/design to best match the application performance requirements, will also help better develop the student's problem-solving and synthesis skills and appreciation for engineering applications. Especially in a context of evolving actuation technology and newer applications, such skills would be highly valued, as there is little by way of documented engineering practice to guide actuation technology selection and actuator design in such emerging areas. Consequently, developing the higher level synthesis skills inherent in the broader approach to control system design is a way for controls engineers to continue to provide value in complex design environments involving emerging technologies as well.

This perspective on control system design education may also be viewed as being responsive to some of the stated requirements for successful industry deployments of new control technology across multiple application domains identified in a recent state of the art review titled "The Impact of Control Technology - Overview, Success Stories, and Research Challenges" (Samad and Annaswamy, 2011), and published by the IEEE Control Systems Society. Quoting from this study: "Despite its maturity as a discipline, control engineering is often a technology that is considered only after the plant has been designed. The design of a plant such that it can be effectively controlled is still rare in many applications." Emerging needs identified include "co-design of plant, sensors, actuators, and control for desired closed-loop performance". The improved awareness on the part of the control engineer of the context within which control is to be exercised that would result from such an approach will also enable development of control algorithms more likely to lead to effective implementations. While the cited study stated the need as common across multiple application domains, we argue here specifically that broadening control system design education to include such co-design of the actuator and the plant, in the application domain of mechanical system control, is important for mechanical engineering students and would allow them to bring more value to their function as control engineers. We consider the status and capabilities of tools for such co-design in the following section.

Practices in specifying control system performance and capabilities of actuation technologies for control applications are reviewed in the following section. An existing unifying framework for representing actuation system capabilities and their selection for applications of interest that is being used with some success in recent years is then presented and assessed. Developments needed for an improved methodology for actuation system selection are enumerated in the final section, and constitute our goals for ongoing work in this area.

2 Practices in Performance Requirements Development and Assessment of Actuation Technologies

Development of detailed control systems performance requirements for specific applications is usually the province of application engineers, requires considerable awareness of all aspects of these applications, and is very much a context-dependent task that varies significantly from one application to another. Documentation resulting from such work is usually information proprietary to the organizations performing the work. As such, this function is best viewed as one that is appropriately learnt on the job and in the context of organization-specific practices. Consequently, the fact that there is little by way of open technical literature on methodologies for performing this function is only to be expected, and the fact that the topic is usually not part of academic curricula is not a shortcoming that we see the need to address here. It is useful however to see how capabilities of competing actuation technologies are assessed or represented in practice, and to see what implications such practices have for the education of control engineers.

Figure 1 represents the relative capabilities of two established actuation technologies, electrohydraulic (EH) and electromechanical (EM), in terms of the power level and speed of response of actuation, as seen by Moog, an aerospace control systems vendor (Maskrey and Thayer, 1978). The lower boundary represented the limits on the capabilities of electromechanical actuation at the time, whereas the upper boundary represented limits on the capabilities of electrohydraulic actuation. The aerospace control applications noted on the figure were amenable therefore primarily to electrohydraulic actuation at the time of the publication of the cited reference. The measures used to represent power level and speed of response were stated therefore in terms meaningful only for electrohydraulic actuation, more specifically, a servovalve or a pump (for hydrostatic drives) controlling fluid flow to an actuator which powered the load motion. Power level was presented in terms of horsepower corresponding to a 3000 psi pressure drop across the valve or pump, or in terms of flow rate in gpm for a valve pressure drop of 1000 psi. The speed of response was presented in terms of the frequency corresponding to which the servovalve frequency response had a 90º phase lag. It should be noted in particular that the axes are in log scale, with multiple decades along each axis.

The association of any named application on the figure with the corresponding power level - speed combination has more significance on how this application compares with another application, rather than the narrowly defined absolute region on the space the application occupies. So, for instance, missile fin position control usually requires much higher speeds of actuator response than aircraft primary flight control and usually involves much lower power levels. The ranges of response speeds and power levels of flight control systems can themselves be wide. While Figure 1 did present useful information on the relative capabilities of different actuation technologies and the relative actuation needs of a variety of applications, its principal utility in the manner presented was in relating applications to the capabilities of the electrohydraulic actuation hardware that would be required for these applications. The perspective was also one of informing the user of these systems, and hence the customer of the control systems vendor, of the appropriateness of the actuation systems for the applications noted. The reliance upon open loop specifications in terms such as flow rates and servovalve phase lag that are related only to electrohydraulic actuation limits the utility of the results in situations requiring evaluation of alternative actuation technologies. In fact, actuation needs of applications are really better stated in terms of closed loop performance specifications on the speed of response rather than open loop specifications, as such specifications can be independent of actuation technology. Such a specification on the actuation closed loop speed of response is used in Figure 2, also reflecting the same control systems vendor perspective (Thayer, 1988) and this representation is therefore more useful. The variety of actuation technologies considered is also broader, and includes electropneumatic (EP) actuation, and electropneumohydraulic (EPH) actuation. The representation serves the purpose of showing that, at the time of the publication, electrohydraulic actuation continued to have significantly more capability than electromechanical actuation for aerospace applications.

Figure 2 is more useful than Figure 1, but it shares a critical lack of transparency on how the limiting envelopes shown for any of the actuation technologies were determined. Since the limiting envelopes are really closed loop system-level characterizations, they depend on the characteristics of all of the system components as well as the control algorithms for the closed actuation loops. Since the component characteristics, and the analysis and design methods used to determine the closed loop control algorithms corresponding to the performance envelopes, are not specified by the hardware/systems vendor, there is a resulting lack of transparency. Taking valve controlled electrohydraulic actuation as an example, the closed loop actuation system characteristic (actuated load dynamics in Figure 2) depends on the characteristics of the servovalve, actuator (e.g. piston or fluid motor), sensor(s), motion converter if used, (e.g. ball screw), and the control algorithm used for closed loop control, and hence depends on a large number of variables related to the actuation that are not specified. Since transparency is important in educational settings, the issue of how best to represent system-level capabilities of any actuation technology meaningfully for a variety of applications, while maintaining transparency, needs to be resolved. We note, however, that the characterization of actuation technology capabilities at the system level, as in Figures 1 and 2, is important and should be retained in any representation of actuation technologies that is used for design support.

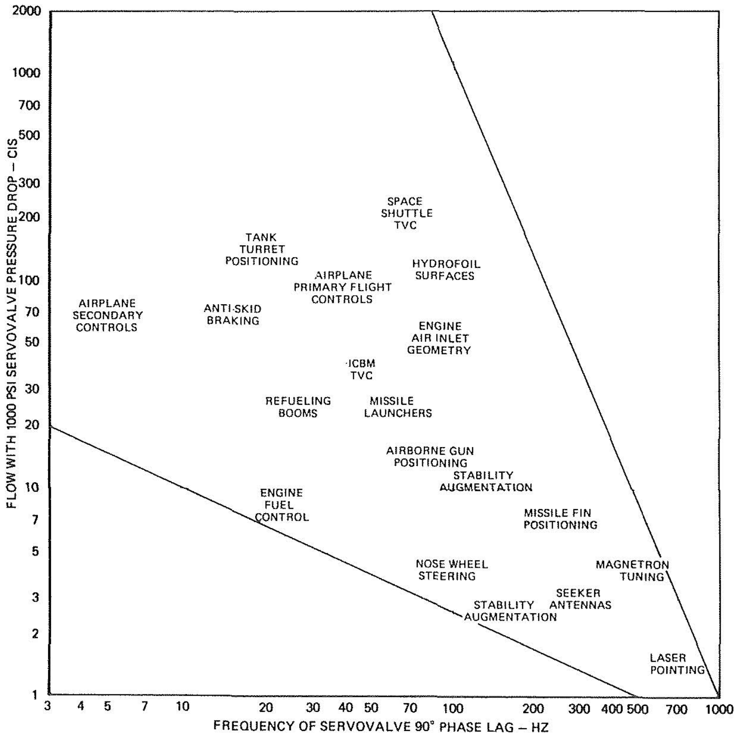

Fig. 1 Aerospace application performance requirements (Maskrey and Thayer, 1978)

Yet another consideration in representing the capabilities of actuation technologies is that different applications require emphasis on different measures of performance. While power levels and speeds of response are highlighted in Figures 1 and 2, applications may emphasize other aspects of performance, such as weight, size, cost, efficiency, duty cycle, reliability etc, and may also allow effective comparison of actuation technologies. Environmental considerations may emphasize other requirements such as temperature, vibration/shock limits, nuclear hardening, EMI etc. Business and support issue considerations such as service requirements, reusability, environmental impact, and ownership are important as well, though they may not all be amenable to quantification. It is important therefore that comparison of actuation technologies accommodate a variety of performance measures.

Other comparisons of different actuation technologies on a set of common performance measures have also been reported, either in the context of a specific application such as robotic actuation (Hollerbach et al., 1992), a specific type of actuation such as microactuation (Fukuda and Menz, 1998) or MEMS actuation (Bell et al., 2005), or by way of comparing one or more emerging actuation technologies with other actuation technologies (Kornbluh et al., 1998). Hollerbach et al. (1992) compare the performance of a variety of technologies for macrorobotic applications including established technologies such as hydraulic (electrohydraulic), electromagnetic (electromechanical), and pneumatic (electropneumatic), and emerging technologies such as piezoelectric, shape memory alloy (SMA), polymeric, and magnetostrictive actuation. The different actuation technologies are considered with a view to understanding the source of limitations on actuation technologies and industrial design and manufacturing practices, and comparisons are done both at the actuator level and at the actuation system level. Typical of the insights into actuation technologies are observations such as i) an electric motor's torque/mass ratio depends on electromagnetic design whereas its power/mass depends also on the limitations of the power electronics and ii) electric motor currents are limited by the motor's ability to dissipate the heat generated at the windings. Representative actuator level comparisons of the different technologies in terms of stress, strain, strain rate (S.R.) and mechanical efficiency (M.E.) are listed in Table 1, the numbers being derived from a combination of sources such as performance data from experimental prototypes, technological limitations, and behavior intended to be 'representative'.

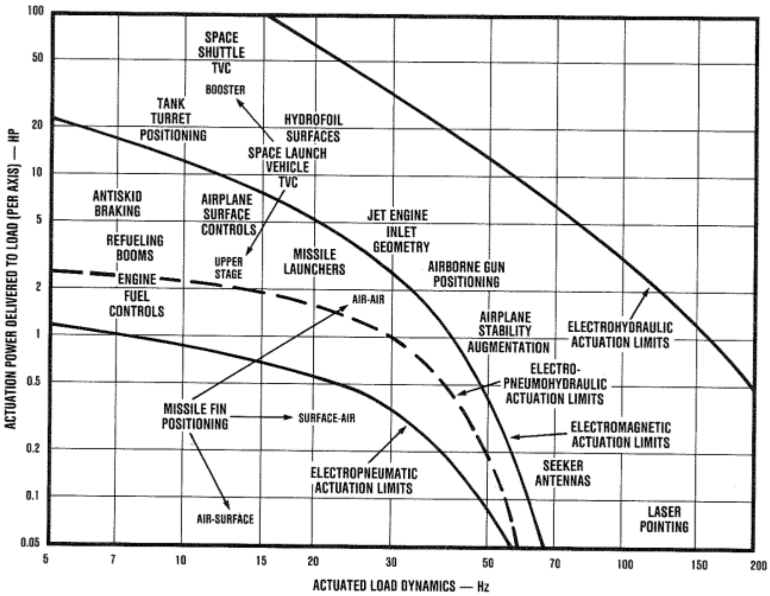

Fig. 2 Aerospace application performance requirements and actuation technology limits (Thayer, 1988)

As compared to the actuation technology comparisons in Figures 1 and 2, there is more transparency behind Table 1. Polymeric actuators have reasonable strain levels as compared to the established macroactuation technologies such as hydraulic, electromagnetic, and pneumatic, whereas shape memory alloys, piezoelectric and magnetostrictive actuation have comparatively good stress levels but lower or much lower strain levels. Shape memory alloy actuation is particularly poor in terms of its efficiency. While these comparisons do provide insight into the relative capabilities of actuation technologies, the comparisons do not extend very readily to more direct and general comparison of their usefulness for specific robot actuation tasks. Torque/mass and power/mass are listed in Table 2 for the different actuation technologies based upon commercial products or prototypes and represent system-level capabilities. Unfortunately, the manner of determination of these system level capabilities does not provide any transparency into the underlying factors and limits their utility in the educational settings we seek to support. Methodologies leading to the compilations of actuation capabilities in Table 1 and 2, and other similar compilations (Kornbluh et al., 1998), while serving well their intended use of comparing actuation technologies broadly for a single application, fall short of providing support for a broader framework for control system design.

Roadmaps for control technology developments are platforms allowing for the collective development of performance requirements for control systems in the application areas of interest. While this task is very much context-dependent, there is some transparency on how performance requirements are developed and more documentation of the underlying methodologies for identifying candidate actuation technologies. Moreover, roadmaps for technology developments perforce address emerging technologies along with established technologies as appropriate, and emphasize system-level capabilities so as to be able to gauge impact on the application area of interest. A recent such roadmap on actuators for gas turbine engines (Webster, 2009) by the Research and Technology Organization of the North American Treaty Organization (NATO) considered actuator requirements for gas path control within the engine in terms of airflow manipulation, flow switching, flow control, and geometry control. Given the mechanical nature of the actuation, actuation technologies were viewed in terms of their technical capabilities such as maximum force, energy density, stroke, response speed or repetition rate, input energy type, resolution/controllability support system requirements, and environment limitations, for example, temperature or pressure. Starting with generic actuation requirements for the gas path control functions noted above, capabilities of established and emerging mechanical actuation technologies were surveyed first, and we'll return later to the topic of how such comparison was performed here. Then, based on a consideration of more specific application-related requirements and developments, an actuation technology roadmap was developed. For each of the control applications considered, significant environmental conditions, requirements on actuator operation constituting a partial list of performance specifications, candidate actuator technologies, current technology readiness level (TRL) and projected timeframe for TRL 6, and actuation challenges were identified. Taking as an example compressor blade tip clearance control, specifications for actuation stroke, velocity, displacement resolution, and force levels, along with frequency of actuation were determined. Pressures and temperatures of operation were also noted. A variety of actuation technologies were identified as candidates, including pneumatic, hydraulic, electromagnetic or electromechanical, and piezoelectric, along with the challenges for each actuation technology. Weight was identified as a potential challenge for hydraulic and electromagnetic actuation, stiffness for pneumatic actuation, temperature and strain level for piezoelectric actuation, seals for hydraulic actuation, and effectiveness of control for electromagnetic and pneumatic actuation. The study also noted that cost was a concern for all of the actuation technologies for compressor clearance control as compared to the more technically challenging problem of turbine blade tip clearance control, as the performance benefits realizable from the former were lower. We argue that awareness of the broader issues involved in comparing actuation technologies in the manner described here would enable control engineers to play a more significant role in the mechanical design tasks related to actuation system design that precede control algorithm design. The goal of the broader control system design education that we advocate is to cultivate such awareness in the control engineer.

Table 1 Typical performance characteristics of actuators (Hollerbach et al., 1992)

Actuator	Stress (MPa)	Strain	S.R. (s^{-1})	M.E.
Electromagnetic	0.02	0.5	10	0.9
Hydraulic	20	0.5	2	0.8
Pneumatic	0.7	0.5	10	0.9
NiTi SMA	200	0.1	3	0.03
Polymeric	0.3	0.5	5	0.3
Piezoelectric	35	0.001	2	0.5
Magnetostrictive	10	0.002	2	0.8
Muscle	0.35	0.2	2	0.3

Table 2 Comparison of actuator characteristics (Hollerbach et al., 1992)

Actuator	Torque/mass	Power/mass
McGill/MIT EM Motor	15 N·m/kg	200 W/kg
Sarcos Dexterous Arm electro hydraulic rotary actuator	120 N·m/kg	600 W/kg
Utah/MIT Dexterous Hand electropneumatic servovalve	20 N·m/kg	200 W/kg
NiTi SMA (Hirose *et al.*, 1989)	1 N·m/kg	6 W/kg
PVA-PAA polymeric actuator (Caldwell, 1990)	17 N·m/kg	6 W/kg
Burleigh Instruments inchworm piezoelectric motor	3 N·m/kg	0.1 W/kg
Magnetoelastic (magnetostrictive) wave motor (Kiesewetter, 1988)	500 N·m/kg	5 W/kg
Human biceps muscle	20 N·m/kg	50 W/kg

3 Assessment of a Unifying Framework for Actuation System Selection

In evaluating the capabilities of different actuation technologies for gas turbine engines (Webster, 2009), the author relied upon a methodology for selection of mechanical actuators developed and reported on by Huber et al. (1997), Zupan et al. (2002), and Bell et al. (2005). We summarize that methodology here. A detailed list of actuator performance characteristics or measures is compiled and shown in Table 3 and used as the basis for actuator evaluation. Ranges of achievable performance characteristics are then estimated for different actuation technologies, based upon manufacturers' data and simple models of how actuator performance is limited fundamentally by basic phenomena such as resonance and thermal response. While tabulation of these ranges of performance characteristics is given by Huber et al. (1997) and is informative, graphical representations of pairs of these performance characteristics such as Figures 3 and 4 may be seen to be more effective visually.

Figure 3 shows actuation limits for different types of actuators in terms of bounds on actuation stress and actuation strain, these performance characteristics and others being defined in Table 3. Logarithmic scales are used on both axes in order to cover multiple decades of the performance characteristics. The boldfaced lines displayed are really the upper right corners of the corresponding actuation limits. Applications requiring high stroke would normally require actuators toward the right of the figure whereas those requiring high actuation stress levels would

Table 3 Definitions of actuator performance characteristics (Huber et al., 1997)

performance characteristic	definition
actuation stress (σ)	The applied force per unit cross-sectional area of an actuator.
maximum actuation stress ($\sigma_{\max}$)	The maximum value of actuation stress in a single stroke which produces maximum work output.
actuation strain (ϵ)	The nominal strain produced by an actuator; an actuator of initial length L extends to a total length of $(1+\epsilon)L$.
maximum actuation strain ($\epsilon_{\max}$)	The maximum value of actuation strain in a single stroke which produces maximum work output.
actuator density (ρ)	The ratio of mass to initial volume of an actuator. (We neglect the contribution to mass from power supplies, external fixtures and peripheral devices. For example, in the mass of a hydraulic cylinder, we include the working fluid and the cylinder, but neglect the compressor, servo-valve, cooling system and mounting fixtures.)
actuator modulus (E)	The ratio of a small increment in σ to the corresponding small increment in ϵ when the control signal to an actuator is held constant. (In general this differs from the measured modulus $d\sigma/d\epsilon$ which depends upon the control signal.)
volumetric power (p)	The mechanical power output per unit initial volume in sustainable cyclic operation.
efficiency (η)	The ratio of mechanical work output to energy input during a complete cycle in cyclic operation.
strain resolution ($\epsilon_{\min}$)	The smallest step increment of ϵ (order of magnitude approximations are given).

use actuators toward the top of the figure. Applications requiring high energy densities would use actuators toward the upper right corners of the figure as they correspond to higher values of the product $\sigma\varepsilon$, constant contours for which are displayed as discontinuous lines with a slope of -1. The discontinuous lines with a slope of +1 represent contours of constant σ/ε, a modulus or stiffness-like quantity, the latter being denoted by E, Table 3. Actuators with their upper right boundaries in regions of high σ/ε also have high modulus values E, and are better suited for open loop applications, whereas those in regions of low σ/ε have low modulus values and require closed loop control in order to achieve accuracy. Inferences based on Figure 3 such as those stated above are valid if actuator sizes are comparable. Figure 4 shows plots of actuation limits in terms of actuation power volumetric density and frequency of actuation, the latter being an open loop measure in this case, and again underscoring the advantages of hydraulic actuation over pneumatic and electromechanical actuation as in Figure 2. There are important differences between Figures 2 and 4, and we note these differences when we later address the question of the utility of these representations for making actuator design decisions as part of the control system design process.

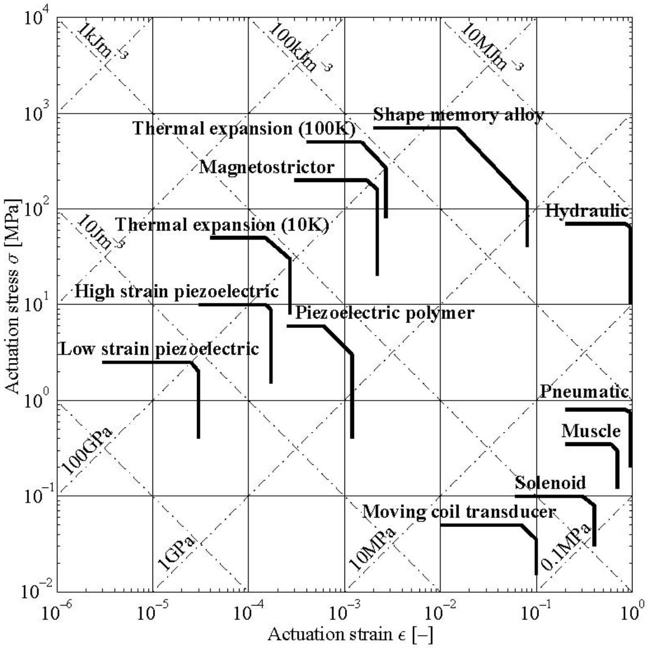

Fig. 3 Actuator performance characteristics: actuation stress and actuation strain (Huber et al., 1997)

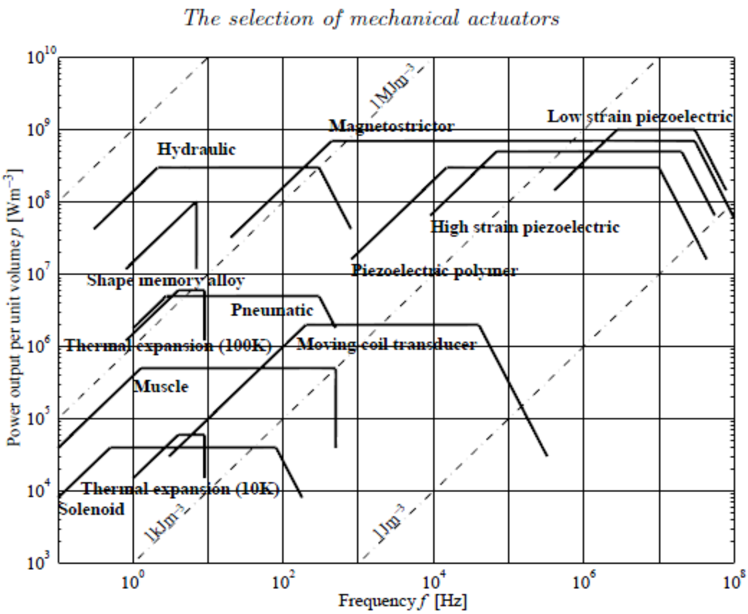

Fig. 4 Actuator performance characteristics: power density and frequency range (Huber et al., 1997)

The utility of the representation of mechanical actuator performance developed by Huber et al. (1997) is that it allows broad comparison of families of actuators based on a variety of performance characteristics, and identification of feasible actuation methods early in the design stage. The framework and associated procedure for actuator selection as it stands currently is however limited in its ability to effectively support design for closed loop control. These limitations, and the enhancements needed to overcome them, are the following. First, closed loop system capabilities depend on more than just actuator performance characteristics. For example, the characteristics of other actuation system components, such as power transmission components and the control algorithm, are relevant as well in determining closed loop system performance. Therefore, the actuator comparison must be extended to performance characteristics of actuation systems so that system level capabilities, preferably closed loop, may be captured in the comparison. Second, we need to classify mechanical actuation applications in more generic terms, and to capture more application requirements in such classification, so that application requirements may map better and more broadly to actuation system performance characteristics. Third, the compilation of performance characteristics for actuators and actuation systems must be more comprehensive in order to incorporate recent and continuing developments in actuation technology. It is also important that better linkages be established to underlying technological limitations so that the compilations have more lasting value. The utility of the resulting enhanced framework would seem to be better suited to evaluation of fewer candidate actuation technologies at a time, suggesting that the enhanced framework might be appropriate for a later stage of the design process after early design decisions narrowing the choice of actuation technologies have been made based on the methodology proposed by Huber et al. (1997) or others of a similar nature. The control system design education context of primary interest here is compatible with such a later design stage and would require the enhancements listed here. We elaborate on these enhancements below.

4 Toward an Improved Methodology for Actuation System Selection and Design

The need for accommodating system level considerations in selecting actuation technologies for different applications, and the limitations of looking only at actuator characteristics for this purpose, has also been noted by Huber et al. (1997) and by Webster (2009), and is the first of the enhancements proposed here. For example, as noted in connection with the definition of 'actuator density' in Table 3, the term excludes system components other than the actuator, an omission that would be significant for weight sensitive applications when considering hydraulic actuation since such actuation requires components other than the actuator, such as the servovalve and hydraulic power supply. The latter is also a resource usually shared by multiple actuators and presumably best dealt with qualitatively in most cases. More importantly, some performance characteristics such as speed of response and resolution are more meaningful for actuation selection when they refer to closed loop system-level characteristics rather than actuator or open loop characteristics. While this poses challenges since control algorithm design decisions are yet to be made, the limitation caused by omission of such system-level considerations has been noted by Webster (2009) in connection with the actuator roadmap for gas turbines, and by Granosik and Borenstein (2005) in their evaluation of actuators for a serpentine robot. The latter reference also augments the actuator characteristics in Figures 3 to include data for pneumatic bellows and electric motors with leadscrew transmissions to convert rotary motion to linear motion, two candidate actuators of interest for the application. Figure 5 shows the result. Actuation system compliance, which is a closed loop system-level performance characteristic, is a significant criterion for the application, and its implications for choosing between electric and pneumatic actuation for this application are dealt with entirely qualitatively in the cited reference, with the final decision to choose pneumatic bellows for actuation being based on the natural compliance of pneumatic actuators.

While this approach may have been appropriate for this application, there are many applications where it is important to be more quantitative in evaluating alternate actuation systems and it is therefore important to formulate a methodology for actuation system selection that can accommodate closed loop system-level performance characteristics more quantitatively. For instance, many of the aerospace applications in Figure 2 were amenable to more than one actuation system solution more than two decades ago as indicated by their

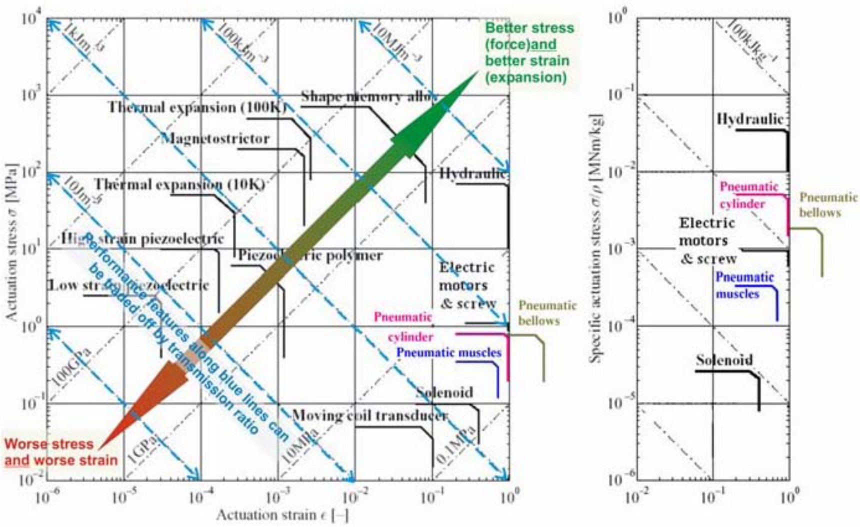

Fig. 5 Actuation system evaluation for serpentine robot (Granosik and Borenstein, 2005)

relationship to the corresponding actuation technology boundaries, and many more are expected to be so today as a result of developments in actuation technologies. The contributions of components to system-level performance in applications of interest therefore need to be accommodated in a manner that supports co-design of the actuation system and control algorithm. It is well known for electrohydraulic servomechanisms, for instance, that the hydraulic resonance resulting from hydraulic fluid compliance and the mass or mass moment of inertia of the load is a limiting factor on the performance of closed loop control systems (Merritt, 1967). In another application domain, machine tool slide motion control, it is similarly known that the axial stiffness of the ball screw transmission system limits the performance of slide motion control systems (Younkin, 2003). It would be immensely valuable for the effectiveness of proposed control solutions therefore, if these limitations on control system performance could be captured in generic form and considered as part of the actuation system selection process. Clearly, doing so would require more considered evaluation of the mechanical actuation context within which the control system is to be function. In an educational setting, the student exposed to such design practices would have a broader and hence more beneficial exposure to control system design.

The second enhancement noted above, and one needed to better support actuation system selection for applications, is to classify mechanical actuation applications in more generic terms so that application requirements may be mapped better to actuation system performance characteristics. Huber et al. (1997) consider a few highly simplified actuation applications amenable to analytical procedures for actuator selection, an example being the selection of an actuator for cyclic oscillation of a mass m at frequency f and motion amplitude X while minimizing actuator volume. The same research group developed actuator selection procedures (Zupan et al., 2002) that used a data base of actuators and their performance characteristics such as those in Table 3, to select a set of feasible actuators based upon threshold values of performance criteria such as actuator weight, actuation frequency, force, stroke, or simple combinations of these performance criteria. The actuator selection from this reduced set of actuators was then performed using analytical procedures to optimize an additional criterion. Both sets of examples applications are highly simplified and not very representative of broad variety of actuation applications of sufficient engineering interest. Other variations on the idea of investing simple contours on the space of actuator performance characteristics with significance for classes of applications were also noted by Huber et al. (1997). For instance, contours of straight lines with slope of -1 on Figure 3 may be seen to correspond to regions of constant work per unit volume, and consequently actuators with their boundary regions in the upper right corner of the figure are appropriate for energy-intensive actuation tasks requiring compactness of actuators. There is considerable scope for improving the extent of mapping of application requirements to actuation system performance characteristics.

We propose to start with consideration of a limited set of actuation applications instead and classify them broadly and generically in terms of their requirements.

Our expectation is that these classifications of application characteristics would either identify new actuator performance characteristics of interest or, alternatively, different combinations of actuator performance characteristics that would be significant for different application categories. To cite a simple example that is known already, applications where inertial loads are dominant would favor actuators with high values of force/mass or torque/inertia as for robotic manipulators. Applications where, in addition, there is a volumetric constraint on the packaging of the actuator, would benefit from actuators with high values of torque/inertia per unit volume. It is important that such a classification effort begin with a consideration of application requirements. In doing this task, we plan to work with application engineers with experience in developing performance specifications in the selected application domains. We had stated earlier that the development of detailed performance requirements for specific applications is a context-dependent task that is currently left to application development engineers. We propose here instead to classify mechanical actuation applications in terms generic enough for the educational context, and discriminating enough in their requirements on actuation to allow the formulation of procedures for actuation system selection and control system design.

The third and final enhancement needed to better support actuation system selection for applications is to enlarge the compilations of performance characteristics by the references noted above, to include more classes of actuators and actuation systems, and to better link their limitations to underlying technological limitations. An example of the proposed extension to other actuators is the addition, by Granosik and Borenstein (2005), of performance characteristics for motor - leadscrew transmissions and pneumatic bellows to the data compiled by Huber et al. (1997) as shown in Figure 5. Motor-leadscrew transmissions, and actuators using linkages to achieve mechanical advantage, need to be included in the data base of actuators because of their prevalence in practice. While compiling larger data bases of available actuators is an appropriate way to do this, it is also important, where possible, to identify technological limitations on actuator performance. By doing so, the capabilities of the corresponding type of actuation may be explicitly bounded with less effort as compared to relying upon an extensive data base to implicitly represent the bound. For example, Huber et al. (1997) note that the operating frequency of piezoelectric and magnetostrictive actuators is limited by the lowest structural resonance frequency. For shape memory alloy and thermal expansion actuators, both of which depend upon temperature change for actuation, the operating frequency is limited by convective heat transfer coefficients. In both cases, the smallest available size of commercially available actuators has been used to determine the maximum operating frequency. For hydraulic and pneumatic cylinders, the maximum sliding speeds that can be tolerated by the seals are limited and, when combined with lower limits on actuator lengths, results in upper limits on the power per unit volume. Upper limits are also imposed upon the pressure in hydraulic and pneumatic cylinders based on practice and considerations of safe high pressure containment. Hollerbach et al. (1992) have noted that motor torque/mass ratios are limited by electromagnetic design limits such as the maximum magnetic flux density and by heat dissipation capabilities of motors which in turn limit motor currents, while motor power/mass ratios are limited further by the volt-amp rating of the power electronics. The same may be expected to be true of other forms of electromagnetic actuation such as solenoids and moving coil actuators (Gomis-Bellmunt et al., 2007).

Recent developments in macroactuator technology have included hybrid forms of actuation such as electrohydrostatic actuators (Frischmeier, 1997) for aircraft flight control surface actuation that are competitive against more conventional forms of actuation. These actuators rely upon electric motors near the control surfaces powering hydraulic motors that in turn power hydraulic cylinders moving the control surfaces. Closed hydraulic circuits at the control surfaces are used for actuation. The reliance upon aircraft-wide electric power transmission (Power-by-Wire) in such systems eliminates the aircraft-wide hydraulic power transmission employed by systems that rely upon electrically controlled (Fly-by-Wire) servovalve-cylinder combinations at the control surfaces, and hence reduces system weight and complexity. One instance of such an actuator consists of a DC motor powering a fixed displacement pump - cylinder combination, the motor speed being varied under closed loop control of the flight control surface. Another consists of a variable displacement pump - cylinder combination at the control surface and driven by a constant speed AC motor, the pump displacement being varied under electrohydraulic closed loop control. Characterization of the performance of such hybrid actuators in terms comparable to more conventional forms of actuation will therefore be of considerable use in control system design for this class of applications, and is included as part of the enhanced compilation of actuator performance proposed here.

In order to demonstrate the benefits of our approach, we propose to develop actuation system selection procedure enhancements and procedures for co-design of actuators and control algorithms for two classes of applications that satisfy the following criteria: they should be established and prevalent enough for a knowledge base of performance specifications as well as multiple commercially supported candidate actuation technologies to be available, and they should be sufficiently demanding of performance for closed loop system solutions to be necessary. We consider aircraft flight control surface actuation (Gee, 1984: Ravenscraft, 2000) and machine tool and robot control (Srinivasan and Tsao, 1997) as two classes of applications that satisfy the criteria. We expect that detailed performance requirements for specific applications are probably not well-documented in the open technical literature, but that the relevant knowledge base can be compiled from practicing controls engineers involved in application development. The resulting methodologies have the potential to broaden control system design education in the manner envisaged, and to enhance the value of our graduates in control engineering tasks in these established application domains. We expect also that, once the benefits of the proposed approach are demonstrated here, the methodologies developed here may be applied to broader classes of applications involving newer forms of actuation, such as microactuation (Fukuda and Menz, 1998) and MEMS actuation (Bell et al., 2005). Both these categories of applications lack the accumulated knowledge base resulting from established practices in industry, and offer the potential for future industrial practices to benefit greatly from the methodologies developed here.

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