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# Ilities Semantic Basis: Research Progress and Future Directions

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## Abstract

This paper summarizes progress on the investigation of an ilities semantic basis. One of the fundamental challenges for developing a clearer understanding of the semantics of “ilities” (sometimes referred to as system qualities) is continuing ambiguity in these terms. Prior and ongoing research on use of a prescriptive semantic basis has resulted in a framework for formulating ility “definitions.” Progress has been made on evolving the semantic basis construct, a translation layer, and ilities metrics. Synergies with other relevant research are explored. Potential application of the semantic basis approach is discussed, including near-term application in education and longer-term application in technical document comprehension of non-technical requirements. Several future directions for ilities research within the systems community are proposed.

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## 1. Introduction

One of the fundamental challenges for developing a clearer understanding of the semantics of “ilities” (sometimes referred to as system qualities) is the current ambiguity in these terms, which are often used colloquially and therefore inherit informal meaning. Use of “ilities” in some technical disciplines extend from well-accepted prescription; however, this has not yet occurred in the systems community as evidenced by the abundance of definition-offering papers with conflicting meanings. One root cause of the ambiguity in technical usage of ilities is that ilities are typically considered one at a time in the literature. Recent research suggests considering sets of ilities has merit [1, 2,

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3, 4]. Further, there is growing recognition of the importance of considering ilities in relationship to other ilities and larger context [5, 6].

Research indicates that at least three semantic fields may exist for the general set of system “ilities” including change-type (e.g., “flexibility”, “agility”), architecture-type (e.g., “modularity”, “interoperability”) and new ability-type (e.g., “auditability”, “understandability”). Identifying and classifying the in-use ility terms into appropriate semantic fields serves to eliminate ambiguity in meaning, usage, and application, as well as to allow for the explicit consideration of trade-offs within the semantic field. A consistent basis within a field can allow for direct comparison of its members. Revisiting the concept of relationships amongst the ilities, the semantic basis can provide a first order approximation to clarify semantic differences amongst ilities within a particular semantic field. A working hypothesis in the research is that that “architecture-type” ilities are enablers for “change-type” ilities [8].

## 2. Approach

A prior ilities study looked at co-occurrence of ilities terms in the literature, with implied dependence amongst terms, resulting in a directed graph that tempts reading causal relationships into the links [3], but the existence of “co-occurrence” cannot describe the nature of the link. As a complementary approach to discovering relationships amongst ilities, prescriptive assertions can be based upon theory or experience, making conceptual leaps in proposing how ilities should relate to one another. Building upon the insights from looking at various approaches for describing ilities, and drawing inspiration from the linear algebra concept of a basis as a spanning set that defines a space, prior research proposed a prescriptive semantic basis for consistently representing change-type ilities within a particular semantic field [4]. Initially conceived as a ten-category basis, the current semantic basis comprised of twenty categories (Fig. 1) is believed to span the change-type ility semantic field.

Prescriptive Semantic Basis for Change-type Iilities																			
In response to "perturbation" in "context", desire "agent" to make some "change" in "system" that is "valuable"																			
Perturbation	Context	Phase	Agent	Impetus Change				Mech	Outcome Change				System	Valuable* (this category is not complete)					
In response to "perturbation" in "context" during "phase" desire "agent" to make some "nature" impetus to the system "parameter" from "origin(s)" to "destination(s)" in the "aspect" using "mechanism" in order to have an "effect" to the outcome "parameter" from "origin(s)" to "destination(s)" in the "aspect" of the "abstraction" that are valuable with respect to thresholds in "reaction", "span", "cost" and "benefits"																			
Perturbation	Context	Phase	Agent	Impetus* (optional)				Mech	Outcome				Abstraction	Reaction	Span	Cost	Benefit		
				Nature	Parameter	Origin	Destination	Aspect	Mechanism	Effect	Parameter	Origin	Destination	Aspect					
optional	circumstantial; required; general; optional	null	optional	null	required	optional	optional	null (this is implied by "parameter")	Optional	null	required	optional	optional	null	optional	required	required	required	required
"name"	"name(s)"		"name(s)"		"parameter"	"state(s)"	"state(s)"		"name"		"parameter"	"state(s)"	"state(s)"		"name"	"threshold values"	"threshold values"	"threshold values"	"threshold values"
none	circumstantial	pre-ops	none	decrease	level	one	one	form		decrease	level	one	one	form	architecture	sooner	shorter	less	more
disturbance	general	ops	internal	same	set	few	few	function		same	set	few	few	function	design	later	longer	same	same
shift	emptp	inter-LC	external	increase	emptp	many	many	operations		increase	emptp	many	many	operations	system	always	same	more	less
emptp	emptp	emptp	either	not-same	emptp	emptp	emptp	emptp		not-same	emptp	emptp	emptp	emptp	emptp	emptp	emptp	emptp	emptp

Fig. 1. Twenty category semantic basis

While a subset of the basis can be used to generate simpler statements, using the twenty categories provides a richer statement. The twenty categories are: perturbation, context, phase, agent, impetus (nature, parameter, origin states, destination states, aspect), mechanism, outcome (effect, parameter, origin states, destination states, aspect), level of abstraction, and value qualities of the change (reaction, span, cost, benefit). Unique choices for each of these categories will formulate the change-type ility statement. Applied to the example of changeability of a stereo system, the resulting statement is shown below in blue text. In this statement, the grey italicized text is included to show the mapping to categories from the basis (Fig. 2).

In response to a loud noise (*perturbation*) late at night (*context*), during operations (*phase*) of system, desire owner (*agent*) to be able to *impetus* {increase (*nature*) the knob angle level (*parameter*) from one state (*origin*) to many states (*destination*) in the system form (*aspect*)} through turning the knob (*mechanism*) that results in the *outcome* {increasing (*effect*) the volume level (*parameter*) from one state (*origin*) to many states (*destination*) in the system function (*aspect*)} in the owner's stereo system (*abstraction*) that takes less than 1 second (*valuable*).

Fig. 2. Constructed ilities statement stereo example

### 3. Translation layer for ease of use

The semantic basis (Fig. 1) with specified semantic fields, while descriptively exhaustive, is not particularly well-designed for ease of use in practice. Recent research investigation has generated a concept for a software-based implementation of the evolved semantic basis that would be designed for usability by practitioners [19]. The resulting early work produced a conceptual design for a proof of concept translation layer, referred to as the “Ilities Semantic Translation Layer Assistant.” An end goal (beyond the scope of the research investigation) would be to produce operational software that is customizable to the domain and specific language of a user’s organization.

When using the envisioned translation layer assistant, as a first step, the user chooses an ilities dictionary. Presently, there are a number of different definition sets for ilities, and the prototype allows the user to make a choice consistent with their own organization. The various elements used in the Ilities Semantic Translation Layer Assistant prototype are in Fig. 3a. Underlying the prototype are core supporting constructs, shown in Fig. 3b.

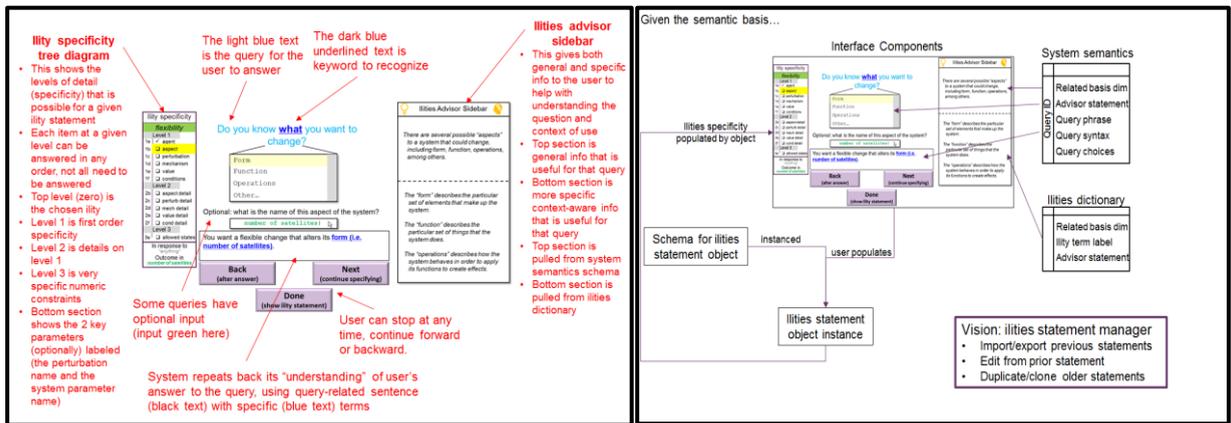


Fig. 3. (a) Elements in the Ilities Semantic Translation Layer Assistant prototype, (b) Core supporting constructs

Following the design of the translation layer assistant, the approach was tested through sessions with researchers and graduate students. The investigation confirmed potential usefulness of such a translation layer, and adjustments were made based on the informal sessions. The scope of the current research precluded more formal testing with a broader stakeholder community, which would be a necessary next step prior to developing a software prototype.

### 4. Ilities metrics and the semantic basis

One of the beneficial outcomes of using the ilities semantic basis as a common representation of ilities is that it can indicate a set of distinct, but related, metrics for measuring three aspects of a given ility: whether it is present, the degree to which it is displayed, and the value of that ility. Since the ility term labels map to particular (potentially overlapping) basis choices, the metrics most cleanly map to the basis choices, and then can be post facto assigned to ility terms. For example, scalability (ability to change the level of a system aspect from one state to another) can be measured in terms of number of states accessible, either as a set, or on a per parameter basis. In fact, the basis can be partitioned into three types of defined factors that impact potential metrics: 1) antecedent descriptions (5 categories), 2) state counting (11 categories), and 3) path valuation (4 categories). Fig. 4 shows the three partitions across the basis.

Perturbation	Context	Phase	Agent	Impetus* (optional)					Mech	Outcome					Abstraction	Reaction	Span	Cost	Benefit
				Nature	Parameter	Origin	Destination	Aspect		Parameter	Origin	Destination	Aspect						
antecedents				states									antecedents		valuation				

Fig. 4. Semantic basis as supplying information for antecedent description, state counting, and path valuation

Using this perspective, appropriate metrics (existence, degree, or value) can be derived for a given ility that is described by a particular ilities statement using the basis. Fig. 5 for example, illustrates several ility labels and whether their specification is sufficient for existence, degree, or value metrics. In this example, flexibility and adaptability relate to antecedent categories (i.e., agent) and therefore are a description of the existence. Their presence in an ility statement is sufficient for existence, but not sufficient to describe degree. For that, we also need to be able to count states (e.g. if we had change mechanisms that describe reachable states). If state counting is supplied, then scalability can be measured. In this example, agility, affordability, and reactivity are defined relative to acceptance thresholds and therefore additional information is needed to measure these (i.e., valuations: how much execution time, cost, and activation time is required for a given change to be acceptable).

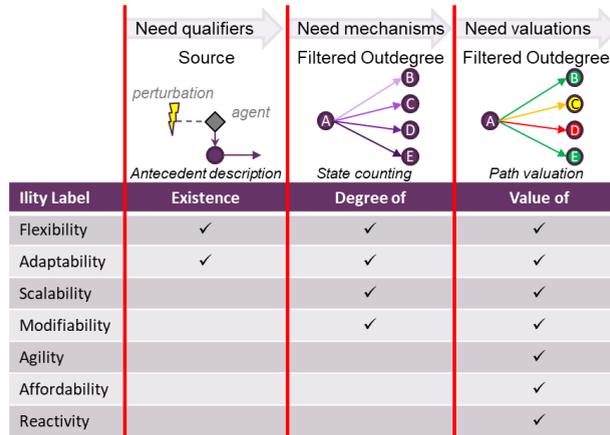


Fig. 5. Example ility label relation to existence, degree, and value of state changes

As seen in the states group of categories, a fair number of basis dimensions relate to state descriptions (e.g., starting point, ending point, desired ranges, etc.). Fig. 6 illustrates this state (point/range) from/to relationship that can be described in the basis, and will fundamentally relate to assessing the “degree of” various ilities.

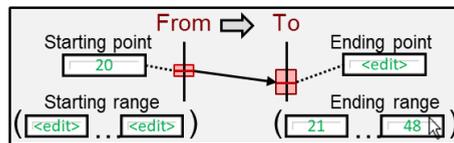


Fig. 6. General state change representation for ilities statement

As a practical workflow, consider the following: First the system aspect is defined (i.e., the state variable) and then (if a tradespace network is available via described change mechanisms) the number of reachable states where that aspect changes can be counted. A series of optional filters can be layered on top of this representation in order for the metric to capture the intent of that ility. For example, if scalability in number of satellites (system aspect, state variable) has constraints in terms of value (i.e., time to make change, cost to make change, time to set change in motion, benefit of end state), then the metric would only count end states and paths that do not violate the constraint.

Fig. 7 illustrates the concept of selective filtering. In this example, consider a starting state A (e.g., satellite constellation), with the existence of an external agent-actuated change mechanism that allows it to change to four other states (B, C, D, E). The antecedent description specifies the existence of flexibility. The existence of states B, C, D, and E allow for “degree of” assessments (here the outdegree, OD, is 4). If we desire scalability, then we look at the end states B, C, D, E and only count those that display a change (up or down) in a state variable of interest (e.g., number of satellites in our constellation). Let’s say state A has 10 satellites, B has 10, C has 15, D has 20, E has 25, then we do not include state B in the filtered outdegree assessment. Our flexibly scalable score would then be filtered

outdegree, FOD=3. But, suppose we want an affordably flexible scalable change and our change cost threshold is “must cost less than \$18M” for change. If path A-C is \$10M and A-D is \$15M and A-E is \$20M, then we do not count path A-E, so this results in FOD=2. So, in summary, this simple tradespace network has described a flexible constellation whose degree is 4, but whose flexibly scalable degree is 3 and whose affordably flexible scalable degree is 2. In this way we can trace ilities to metrics and compare alternatives on a common basis.

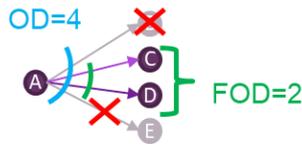


Fig. 7. Example selective filtering of outdegree

Since the change-related ilities fundamentally relate to change (i.e., over time), they are particularly useful concepts within the Epoch-Era Analysis (EEA) framework. In particular, multi-epoch analysis lends itself to assessing the impact of changing perturbations on states and their values. This means robustness can be assessed across considered epoch shifts (i.e., perturbations), and the value of changeability can be assessed as well (since we may have additional context-dependent information on the value of end states). The valuation approach to strategic changeability (VASC) [10] is one example method for leveraging EEA to develop quantitative measures for ilities.

Fig. 8 illustrates how analyses can be layered in order to provide sufficient data to quantify variation in metrics in response to epoch and era changes. In particular, perturbations and contexts dimensions within the semantic basis map to epoch shifts and era progression in EEA. State variables of interest (e.g., form or performance) can be used along with measures of value to determine the degree and value of being insensitive to considered uncertainties. In this way, robustness is a counter point to changeability (i.e., “don’t change”) yet at the same time enabled by changeability (i.e., execute change options in order to preserve outcome state variables within some tolerance). The additional nuances of path valuations (i.e., how long it takes to execute a change) can be highly context dependent (consider across epoch variations) and path dependent (consider across unfolding eras), therefore using an EEA framework can lend credibility and fidelity to assessments of ilities.

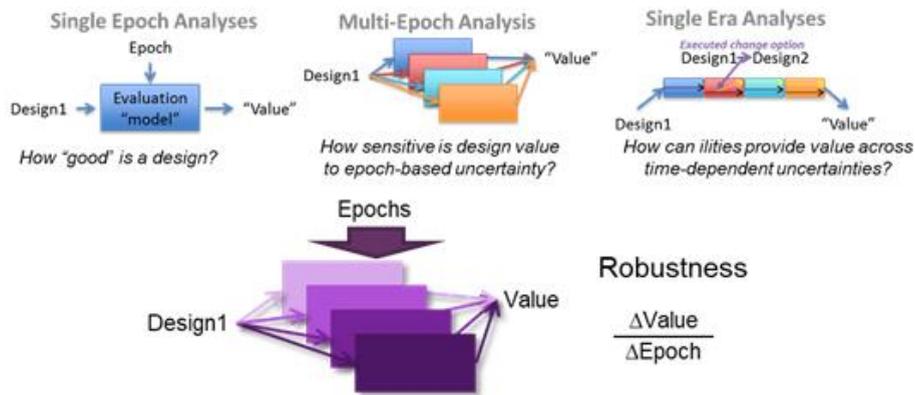


Fig. 8. Example use of multi-epoch analysis to quantify robustness

### 5. Potential future applications for the semantic basis

Potential applications for the semantic basis have been considered throughout the ongoing research effort. One promising area is using the semantic basis for educating students and practitioners about ilities (or system qualities). A longer-term application would involve further research and method development for the purpose of automated technical document comprehension of ilities (or system qualities) using a prescriptive semantics basis.

### 5.1. *Using semantic basis for educating students and practitioners*

Formal education of systems engineers takes place at many universities across the globe. Additionally, there is a vast body of continuing training available to practicing engineers. Given lack of accepted common definitions of ilities, or system qualities, engineers learn the definition that is used by the educating organization or instructor. Naturally, this is a complicating influence on converging on common terms, or even harmonizing the terminology. Additionally, the student learns the definition as written text, and often does not acquire an enriched understanding of the ilities term. In the current research, the application of the semantic basis approach to education is being explored in further detail. Given initial usability testing, the semantic basis appears to be useful for purposes of discussing ilities in a more comprehensive manner. In the classroom, the semantic basis could be used to construct ilities statements using text from a document, to develop a statement such as illustrated in Fig. 2. Our research suggests the semantic basis could be a useful approach to developing a more precise understanding and appreciation of what is required in an ilities statement. Use of various versions of the basis (e.g., 10-dimension basis, 14-dimension basis) and classroom use of a translation layer assistant may provide a means to show how simple statements can be elaborated as more information is gained. It is hypothesized that use of the semantic basis in educating students will enable more critical thinking than simply teaching students simple definitions of ilities.

### 5.2. *Automated Technical Document Comprehension of Ilities using a Prescriptive Semantics Basis*

A much more advanced application of the semantic basis has been identified as a promising longer-term research direction. Desired and emergent system properties (“ilities” or “system qualities”) are universal across domains, enabling system responsiveness on multiple timescales. While ilities sometimes emerge unexpectedly in operational systems, the ability to design ilities properties into systems in advance will be the true game-changer. The lack of a common basis for ilities across domains and disciplines, however, inhibits the ability to predictively make decisions to impact these properties. This limits the discovery of the larger patterns that enable individual and cross-domain design decisions that result in the desired ilities manifesting at the systems level. While ilities-related terms are increasing prevalent in technical documentation for defense systems, their precise description remains elusive. Flexibility, agility, and resilience are three examples of the numerous ilities that are often imprecisely articulated and comprehended differently across stakeholder communities, disciplines and domains [1]. The nature of modern defense systems necessitates being able to translate ilities information across an increasing number of domains and disciplines (e.g., computer science, politic science, cognitive science), driving the need for a ‘Rosetta Stone.’

Given this motivation, the prescriptive semantic basis appears to be a useful structure for supporting automated extraction of a comprehensible ilities statement from technical documents. Further, research in the computer science community opens new possibilities for automatic extraction and methods to structure and analyse a comprehensible ilities statement. Examples include Natural Language Processing (NLP) for extraction [11] and Lightweight Formal Methods (LFM) for structuring and analysing [12].

Such a proposed application of the semantic basis has several areas of potential impact. First, the automated extraction of comprehensible ilities statements during tasks such as capability requirements assessment can reveal and enable comparison of ilities (e.g., flexibility, agility) found in documentation for existing and planned systems, thereby informing decisions. Second, the ability to rapidly generate design concepts in support of repurposing system capabilities could be facilitated by generating options through automated composability of ilities semantic fields (akin to a recommender system for the systems designer/decision maker). Third, there would be potential to augment human decision-making with curated libraries of ilities statements that can be queried with questions normally taking significant time to investigate. For instance: What are all the facets of how my current system supports agile operations? What architecture ilities (e.g., modularity) have been used in space communications systems to enable resilience?

Application of the semantic basis for this purpose may enable the following: ability to automatically extract technical content from text documents using an ilities prescriptive semantic basis, yielding rich, non-ambiguous ilities statements that convey precisely what is meant; and ability to automatically synthesize change-type ilities and architecture-type ilities semantic field information from multiple documents to generate new design concepts (e.g., concepts for achieving a specific aspect of system flexibility through modularity approaches).



For example, MIT semantic basis researchers take a technology system-centric perspective and USC researchers take a software-centric perspective, perhaps resulting in the different choices for aspect (e.g., “form”, “function”, and “operations” for MIT, and “form” and “scope” for USC). Reconciling and harmonizing these perspectives has promise for further maturing the underlying basis and its applicability across a broad range of system types. In particular, this approach can be used to force clarification discussions on distinctions among the basis choices (either implied, or expressly considered), potentially resulting in new ilities of relevance. For example, the USC ility term “contractability” appears to be similar to “scalability-down.” The result of this comparison is that the choices for the basis dimensions may be dependent on domain of interest (e.g., hardware versus software), and similar ility term labels can clearly map to different choices in the basis, highlighting opportunities for further technical clarifications.

## 7. Discussion and future directions

Several future areas of research for the ilities semantic basis include extension of the semantic basis approach for other ilities types, cross-comparison of the semantic basis approach with other emerging approaches, and application of the semantic basis in additional use cases. Validation of the usefulness of the semantic basis is needed, including case studies across different types of systems, pilot project use on one or more existing systems programs, and experimenting with applying the basis in classroom education. The terminology and approach should be compared against current standards and formal guidance documents.

The ilities semantic basis research aims to stimulate broad discussions and research around developing a basis (or bases) as prescriptive instrument(s) for spanning semantic fields whose union consistently encompasses sets of “ilities.” The envisioned end result is that practitioners can have a consistent and (potentially) more complete list of possible ilities to consider for their systems. From a practice standpoint, the semantic basis research is focused on finding a means to assist in generating verifiable requirements and system specifications. Significant further investigation is needed to mature this work, including further comparison, alignment and harmonization with other ilities work in the systems community. In parallel, research is needed to refine and implement a “translation layer” for more natural interaction with the basis, as discussed in section 3.

With maturation of the semantic basis there are opportunities for more extensive application. As discussed in section 5.2, there may be merit in applying a semantic basis approach to enable technical comprehension of existing specifications and documents, in regard to non-technical requirements. Moulton et al. (2015) explored use of semantic technology in automated extraction of text from documents [14]. Future work is needed to test the usability of an ilities semantic basis for similar purpose, as well as how to go beyond extraction to technical comprehension.

Continuing research is needed to further understand the various emerging ilities classifications and frameworks. The DoD SERC has provided the opportunity for many researchers to share and collaborate on ilities research. Dou et al. (2015) brought SERC researchers together to investigate an embedded theory systems (ETS) approach, which included applying ETS to the semantic approach [15]. According to these authors, the goal of the work is “to enable system developers to think and to communicate more effectively than they can today about system properties, underlying design decisions, and stakeholder value.” The formalism of the ETS approach and its application to the ilities semantic basis as a case study provided many new insights and additional research questions. It validates the value of collaborative efforts to build understanding and harmonize approaches.

There are additional promising opportunities to compare and bring together research on ilities, beyond the work of the SERC project. For example, recent work by Colombo et al. (2016) proposes a unified vocabulary based on an extensive literature survey and provides analysis of nine change-related ilities frameworks [16]. The relationship of this work to the ilities semantic basis approach has yet to be explored.

Future research is needed on the area of ilities quantification and metrics. Some limited investigation has been performed (e.g., Refs [10, 17]), but recent focus on ilities has been on characterization rather than measuring. And, the ilities semantic basis research has included initial exploration of various metrics for change-type ilities. Turner et al. (2017), in their recent systematic review of the literature, found that “quantitative measures of the ilities are uncommon” [18]. These authors identify and summarize various approaches to quantifying ilities, in particular for robustness, interoperability and agility. They found that robustness has a variety of quantifications but recommend further efforts for interoperability and agility [18]. To date, the systems community has had relatively little collaborative engagement on the topic of ilities quantification.

Research on the characterization of ilities (system qualities) has been ongoing for more than a decade but has yet to reach a point of convergence. As a community, research progress has been made toward increasing the structure and formalization of ilities terms, and the semantic basis approach is one contribution to this goal. There are many promising research directions related to ilities for the community to collaborative engage, which grow increasingly important given the technical and non-technical challenges facing the engineering of systems for the future.

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