A Systematic Review on Uncertainty in Cyber-Physical Systems

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***Abstract---* Uncertainty is an intrinsic property of any cyber-physical system(CPS), therefore handling uncertainty during the operation of a CPS is a necessary requirement for a CPS. Design, development, and testing of modern CPS is a rapidly expanding research area. However, uncertainty handling is still relatively unexplored. The first step towards handling uncertainty is to identify, define, and classify uncertainty at various levels of a CPS. The aim of this systematic review is to capture the present state-of-the-art of uncertainty modeling in cyber-physical systems. We define appropriate inclusion and exclusion criteria for the studies to be used in this review and extract data from selected studies, and present in this paper.**

From our selected studies, we find that two major lines of research exist in this area, and the ultimate objective of both research directions is to develop the uncertainty-aware test-modeling framework. The first research direction from the simula u-test group [1,6], who first developed a model of uncertainty based on UML, called the U-Model, then they extended model-based testing (MBT) to the purview of CPS via extending the UML profile of Modeling and Analysis of Real-time and Embedded Systems (MARTE) by adding a set of new UML libraries. We focus on exploring the fundamentals of U-Model in this paper. The second approach is to apply methods from Formal Verification of hardware and software systems to CPS [5,7]. This approach also strives to model and verify the uncertainties of known and unknown types in a CPS. We find the first approach more general and hence more applicable to all types of CPS. Finally, as our novel contribution to this line of research, we extend U-model for certain specific use cases.

Keywords*— *Systematic Review, Cyber-Physical Systems, uncertainties, modeling, UML, adaptive, verification, validation, embedded systems, simulations

Introduction

Various safety and mission-critical systems are inherently dependent on cyber-physical systems due to their design [2,3,4]. CPS is critical to the daily function of human society over the entire planet. Hence, it is crucial for such systems to operate reliably. However, since the physical operating environment of CPS is inherently complex and unpredictable, operating under uncertainty must be baked into the design of CPS. We loosely define uncertainty as a lack of knowledge about timing and nature of inputs, state of the system, and consequence of such inputs and any other non-predetermined factors.

Even though CPS is a very active research area, uncertainty in CPS is still relatively unexplored. The ultimate objective of uncertainty in CPS research is to come up with a systematic testing model to certify whether a particular CPS can tackle a range of known and unknown uncertainties. This requires a CPS model that embraces uncertainty. Describing such a model is the primary research question for this systematic review.

We first define the appropriate inclusion and exclusion criteria of studies for this research question in specific, and then extract and analyze the selected studies in-depth. We find that two primary research approaches to this problem in current literature. Section 2 covers this aspect of the review.

The first approach adopted by researchers in the simula u-test group based in Norway, this approach builds a model of uncertainty for a target CPS itself first, and once that model is refined for the targeted application, they apply model-based testing techniques from existing research. The key contribution of this research is the UML based uncertainty model. We explore this model and its applications for the uncertainty test (U-Test) framework in section 3.

The second approach comes from the domain of verification as applied to hardware and software systems. If we can verify a property of a system over its entire possible state space, then we can predict behavior in the presence of uncertainties. This is achieved in a formal verification domain via techniques such as symbolic simulation. However, this approach has inherent scalability issues due to the state-space explosion, unlike the first approach. We explore this approach in-depth in section 4 and finally conclude the paper in section 5.

Section 1: Inclusion and Exclusion criteria definition and Study Selection

There are several research efforts pertaining to modeling cyber-physical systems, but only a small subset of that research is dedicated to model uncertainty in such a system. Notable research work in this field involves the u-test work from Simula Norway [1,6]. Formal verification-based approach from TU Kaiserslautern [5,7]. A very recent Ph.D. thesis also discusses aspects of reasoning under uncertainty in cyber-physical systems [8]. A discussion of uncertainty in the very specific setting of IoT infrastructure can be found in [9].

The primary research question is to describe a model for CPS that has uncertainty built-in. Based on this research question, we defined our inclusion criteria of a study as it must include a model for CPS under uncertainty. Rejection criterion was any study that did not produce a model.

Based on the laid down criteria the following research articles were selected for further data extraction

Criterion	Research articles meeting criterion
Acceptance: must define the CPS model with factoring uncertainty	u-test/model [1,6] formal verification approach [5,7]
Rejection: no modeling	Mathematical reasoning [8] IOT uncertainty [9]

Among the selected studies, two main approaches of modeling were found. The first one is via an extension of UML modeling (U-model), while the second approach extends the formal verification definition of uncertainty.

Section 2: Conceptual U-Model and its applications

Uncertainty is an intrinsic property of a majority of technical systems which is a superset of cyber-physical systems. The objective of this paper is to identify, define, and classify uncertainties at various granularities of CPS.

The research outlined in [1] formalizes a conceptual model of uncertainty which is designed ground-up for CPS. Uncertainty in CPS is a relatively unexplored area. Hence the conceptual model was inspired by existing work on uncertainty in other fields.
The conceptual model is mapped to three levels of CPS:

1. Application
2. Infrastructure
3. Integration

In this approach, the model is captured using UML class diagrams. Two industrial case studies were uncertainties that were identified, classified and specified. This paper defines a conceptual uncertainty model for CPS (referred to as U-Model) with the following objectives:

1. Provide a unified and comprehensive description of uncertainties to both researchers and practitioners alike
2. Classify uncertainties with common representational pattern
3. Provide a reference model for systematically collecting uncertainty requirements
4. Serve as a methodological baseline for modeling uncertain behaviors in CPS
5. Provide a basis of standardization of the conceptual model leading to its broader application in practice

To verify the completeness and validity of the U-model, the authors validated against 2 industrial case studies. The authors performed systematic empirical validation over several stages and revised the U-model alongside the set of uncertainty requirements. The finalized version of the U-model from this set of refinements is presented in this paper.

2.1 Definitions:

CPS is defined as a set of heterogeneous physical units (e.g., sensors, control modules) communicating via heterogeneous networks and potentially interacting with applications deployed on cloud infrastructures and/or humans to achieve a common goal.

Conceptually uncertainty can occur at the following three levels:

1. **Application-level:** Due to events/data originating from the application of the CPS
2. **Infrastructure level**: Due to interactions, including events/data among physical units, networking infrastructure, and/or cloud infrastructure.
3. **Integration level**: Due to either interaction among uncertainties at the first two levels or just from the interaction of those two levels alone

2.2 Conceptual Model of Uncertainty: The U-model explored in this paper consists of a Belief Model, Uncertainty Model and Measure Model that are connected with each other [see Figure 1]

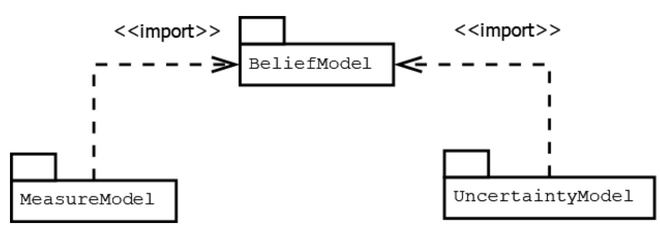

Fig. 1 Top-level domain of the U-Model

Belief Model:

The U-Model takes a subjective approach to representing uncertainty, which implies uncertainty is modeled as a state (i.e., worldview) of some agent or agency – referred to as BeliefAgent – which is incapable of possessing complete and accurate information about some object of interest, due to presence of uncertainty.

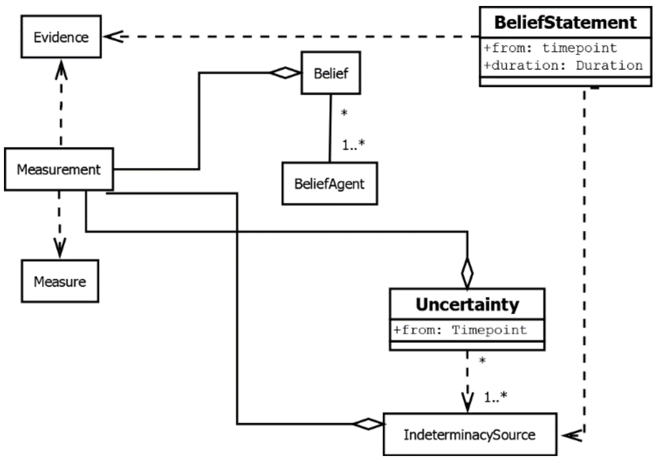

Fig. 2: Core Belief Model

Since perfect knowledge is unavailable, a BeliefAgent possesses a set of subjective beliefs about the subject. These beliefs may either be *valid* or *invalid* depending on whether they represent facts. A Belief is an abstract concept but it is expressible in a concrete form via a collection of explicit BeliefStatements. Different BeliefAgents may hold different views about a given subject; hence each BeliefStatement is associated with a particular BeliefAgent.

The core concepts of the U-Model can be represented as a class diagram where subjective concepts are represented as grey-filled boxes, while objective concepts are represented as unfilled boxes in Figure 2. Subjective concepts are manifestations of the imperfect knowledge of a BeliefAgent, while objective concepts reflect objective reality and are independent of BeliefAgent uncertainties. Subjective concepts can change as uncertainties are resolved over time.

Uncertainty represents a state of affairs whereby a BeliefAgent does not have full confidence in a Belief held by it. This may be due to various factors: lack of information, inherent variability in the subject matter, ignorance, or physical phenomena. Even though uncertainty is an abstract concept, it can be expressed subjectively by the degree of uncertainty held by the agent to a BeliefStatement. The model is intentionally made very general, which makes it extensible and customizable.

Belief: A Belief is an implicit subjective explanation or description of some phenomena or notions held by a BeliefAgent. This is an abstract concept whose only concrete manifestation is a BeliefStatement.

BeliefAgent: A BeliefAgent is a physical entity owning one or more Beliefs about a phenomena/notion. A BeliefAgent can take action based on its Beliefs.

BeliefStatement: A BeliefStatement is a concrete and explicit specification of some Belief held by a BeliefAgent about possible phenomena or notions belonging to a given subject area. A BeliefStatement can be an aggregate of multiple sub-BeliefStatements or require pre-requisite BeliefStatements.

Evidence: Evidence is either an observation or a record of a real-world event occurrence or alternatively could be the conclusion of some formalized chain of logical inference that provides information that can contribute to determining the validity of a belief statement.

EvidenceKnowledge: EvidenceKnowledge expresses an objective relationship between a BeliefStatement and relevant Evidence. It identifies whether the corresponding BeliefAgent is aware of the appropriate Evidence.
An agent may either be aware that it knows something (KnownKnown), or it may be completely unaware of Evidence (UnknownKnown). This is formally expressed by the two constraints attached to EvidenceKnowledge.

Context: EvidenceKnowledge

Inv: self.type = KnowledgeType:KnownKnown or self.type = KnowledgeType:UnknownKnown

Indeterminacy: Indeterminacy is a situation whereby the full knowledge necessary to determine the required factual state of some phenomena/notions are unavailable.

IndeterminacySource: Factors that lead to uncertainty are referred to as IndeterminacySources. A source of information necessary to ascertain the validity of a BeliefStatement could be intermediate in some way, resulting in uncertainty being associated with that statement, one possible source of indeterminacy being another BeliefStatement itself.

Context: BeliefStatement

Inv: Self.uncertainty → forAll (u:Uncertainty | self.IndeterminacySource → includesAll(u.Source))

IndeterminacyNature: IndeterminacyNature represents the specific kind of indeterminacy and can be one of the following:

1. InsufficientResolution: available information is not precise enough
2. MissingInfo: The full set of information about the phenomenon in question is unavailable
3. Non-determinism: The phenomenon is practically or inherently non-deterministic
4. Composite: Combined effect of one or more from the top three

5. Unclassified : Indeterminate reasons

IndeterminacyKnowledge: IndeterminacyKnowledge represents an objective relationship between an IndeterminacySource and the awareness that the BeliefAgent has of that source.

Context: IndeterminacyKnowledge

Inv: self.type = KnowledgeType: KnownUnknown or self.type = KnowledgeType: Unknown:Unknown

KnowledgeType:

1. KnownKnown: BeliefAgent is consciously aware of some relevant aspect
2. KnownUnknown: BeliefAgent understands it's ignorance about some aspect
3. UnknownKnown: BeliefAgent is not explicitly aware of some aspect, yet it is factored in
4. UnknownUnknown: BeliefAgent is completely unaware of some relevant aspect

Measurement: Optional quantification that specifies the degree of indeterminacy of the Indeterminacy source. Currently, U-Model handles 3 different measures: Probability, Ambiguity and Vagueness.

Measure: Objective concept specifying methods of measuring uncertainty.

2.3 Uncertainty Model: This model is an adjunct to the Core Belief Model. Uncertainty has a self-association in this model which facilitates modeling.

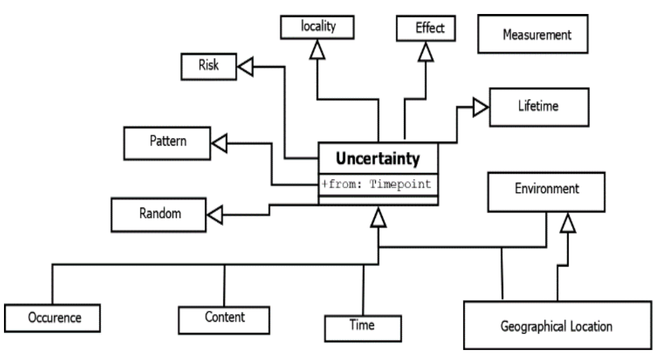

Fig. 3. Core Uncertainty Model

Uncertainty: Uncertainty is specialized in the following topics:

1) Content: BeliefAgent lacks confidence in content existing in BeliefStatement
2) Environment: BeliefAgent lacks confidence in the surroundings of a physical system expressed in BeliefStatement
3) Geographical Location
4) Occurrence
5) Time

Lifetime: Interval of time during which Uncertainty exists

Pattern: Conceptual model for the occurrence pattern of uncertainty.

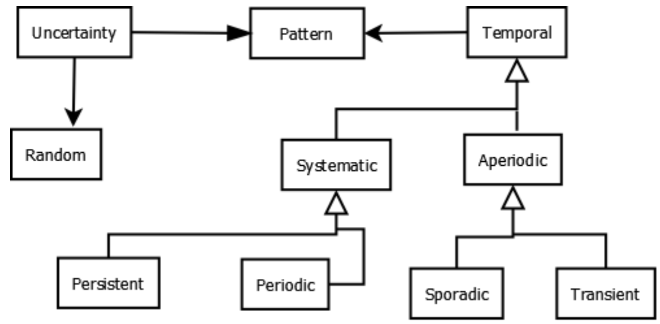

Fig. 4. Patterns of Uncertainty

Locality: Locality is a particular place or a position where an Uncertainty occurs in a BeliefStatement.

Risk: This quantifies the risk associated with uncertainty; high-risk ones may deserve special attention.

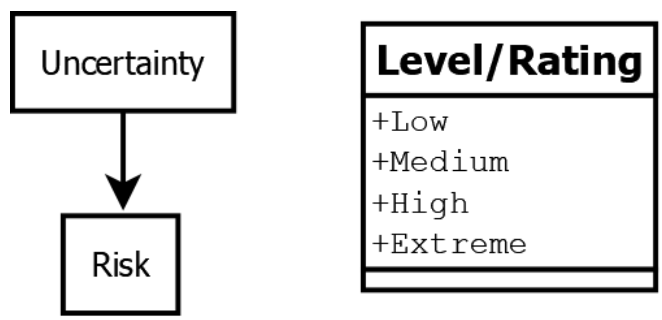

Fig. 5. Risk of Uncertainty

2.4 Measure Model: An uncertainty can be described ambiguously. The ambiguity can be in measurement. Another common way of measuring uncertainty is in vagueness, which can be further classified into Fuzziness and non-specificity. Another way of expression is probability.

It is very crucial to manage uncertainty in a smooth way. Since the CPS are unpredictable in nature hence more priority is given to the designing of such systems. The development and operations of such systems are crucial when considered in terms of unpredictable situations. The validity and the completeness of the UML U-Model are verified and completed by using two industrial application domains – Automated Warehouse and GeoSports. This validation is done in several stages. It is found that more than half of the uncertainties are not identified in the earlier stages of the specifications.

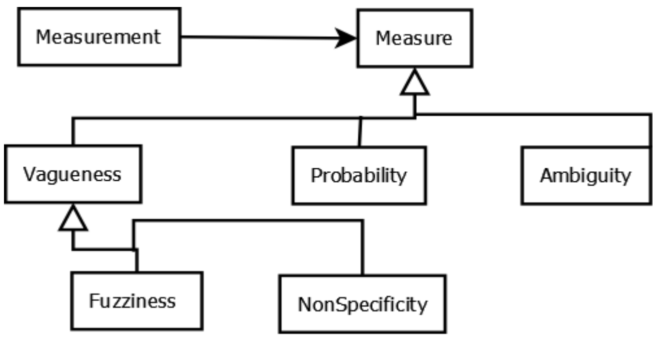

Fig. 6. Measure Model

2.5 A case study for Cisco Virtual Conferencing System (VCS):

Table 1: Illustration of U-Model in context of a VCS

The authors of [1] illustrated U-Model in the context of a real-world CPS namely a virtual conferencing system (WebEx) run by Cisco. Table 1 presents a summary of this model.

2.6 Uncertainty-Aware Test Modeling for CPS:

One of the methods to ensure that the cyber-physical systems handle uncertainty properly is by testing the system using model-based testing techniques. However, the existing testing techniques do not ensure that the capturing of the uncertain behavior with respect to environmental uncertainty. Therefore another technique named Uncertainty-wise testing modeling technique is introduced. This is done in order to create test ready models. Test ready models are the models that represent the expected behavior of the cyber-physical systems. CPS is vulnerable with respect to the uncertainties they face while operating.

Uncertainty Test Modeling framework which is termed as UncerTum, is discussed in [6]. This is based on the conceptual uncertainty model for CPS discussed thus far and is a UML model-based. This profile is divided into three main parts namely Belief, Uncertainty and Measurement profiles. It also consists of an internal library. The main libraries are Uncertainty Pattern Library, Time Library and measure Library.

UncerTum is implemented by IBM Rational Software Architect. With UncerTum, two case studies are shown; one of them is from the real world and the other open-source case study from the literature. Three perspectives are evaluated with the help of UncerTum which are the correctness of the developed models, Completeness and Coverage of the profile and the effort which is required to model the uncertainty with respect to the number of model elements and time.

CPS is sometimes defined as a heterogeneous system and is connected via a heterogeneous network. In order to look in more depth into uncertainty in CPS, they have developed the UML model. This is a conceptual model and it is done in order to define uncertainty and associated concepts. There is also an extension of the U-Model concepts and this is done in order to support the model-based testing of all the levels of cyber-physical systems.

UML concept was taken into light after much research on the cyber-physical systems in the various domains of healthcare systems, physics, philosophy etc. The advantage of the UML test profile is that under the circumstances of the expected behavior of the system, it can be modeled. And after that various test cases can be generated. Test generators are employed in order to carry out various test cases. UTP also has the advantage of describing the behavior of the systems when there are test cases. The test-related concepts are introduced like the Test data, Test Design model, Test case. This is introduced in order to enable the generation of test cases automatically. The updated and latest version of the UTP profile is UTP V.2.

Package	Concept	Explanation
BeliefModel	Level	Application
	BeliefAgent	Software Testing Engineers
	BeliefStatement	VCS dials to another VCS 70% of the time
	Indeterminacy Source	Improper human behavior where he/she enters the incomplete name
	Evidence	Execution of 100 test cases
	Uncertainty	Uncertainty in whether dial to another VCS will be successful or not.
UncertaintyModel	Type	Occurrence
	Lifetime	The difference in the time the dial was initiated and response from the system was received
	Locality	Invocation of the dial API of VCS
	Pattern	Derived pattern from the collection of values of a lifetime of uncertainty
	Risk	Low
MeasureModel	Measurement	70% of the time derived from Evidence-based on test execution history
	Measure	Probability

In this version there are five packages on concepts namely Test Analysis and Design, Test Architecture, Test Behaviour, Test Data, Test Evaluations, This framework is only meant for supporting the test cases mainly the test ready models are created and these, in turn, are used in generating executable test cases. Modeling for the automated code generation is much more detail-oriented as compared to the above modeling owing to the fact that test modeling is used only to model the test interfaces and the behavior of the system. While developing the profile, UML concepts are hired mainly: uncertainty, belief and Belief Statement. The framework is composed of CPS testing profiles.

The Belief part of the UUP is the key component as it focuses on the subjective uncertainty. Another key component of UUP is the deployment of the concepts of uncertainty. Out of the measure libraries, three major packages are discussed namely probability, ambiguity and vagueness in order to enhance modeling. Uncertainty remains the same until and unless any further approaches are taken in order to deal with it. On the other hand, one cannot guarantee that uncertainty will get resolved and thus in some cases, it remains forever. Forever is coined in order to show the execution of the test cases. The methodology of modeling is organized from the perspective of three main types of stakeholders: application modeler, infrastructure modeler and integration modeler. In the application level modeling it is composed of creating application-level class diagrams, creating application-level state machines, application of CPS testing level profile, and finally applying the UUP notations. The class diagrams capture the attributes of the application level. These values can be accessed in a direct way. In a class diagram, each of the classes has its attribute which captures a system attribute. Each operation in the class shows an API. It may represent an action that is generated by the operator. Each of the signals shows the stimuli. These stimuli are received from a different state machine. The infrastructure level modeling is different from the application level modeling in the sense that the attributes here capture the observable infrastructure attributes unlike the application -level. In the case of the integration level model, much focus is given in the interaction between the application level and the infrastructure level modeling. One of the ways to define the elements in the integration level modeling is by creating state machines and then by bringing new elements to them. The advanced feature of the state machines is helpful like the concurrent state machines. State machines are required to be consistent in nature.

Modeling measurements are very vital to measure BeliefDegree, Uncertainty, InterdeterminacyDegree, Risk, and Effect. It is shown here that test ready models are syntactically correct and the communication takes place in a correct fashion as well. Now by using test modelers, accidental errors might get introduced. So, validation is done in order to check the errors. After the validation process is completed and the errors are eliminated test cases are started after that. Now the data executes the trigger in the test ready models. Random values are generated when a trigger is guarded with a guard condition. These values satisfy the guard condition. Eventually, these values are employed to fire. However, in another case, random values for the parameters of the event like Call/Signal gets generated if the trigger is not guarded. Another case random values get generated which satisfies the change condition only if the trigger matches with the ChangeEvent. Now when the trigger matches with the TimeEvent, we can relate that the event gets lapsed during that certain time.

Section 3: Formal Verification approach to CPS uncertainty:

CPS is not restricted to only one domain, and it is indeed very diverse. It is not only a part of critical systems but is used in other domains as well. In CPS, the software monitors the physical components. It has the software and hardware components. Even though it's not possible to avoid failures, the different changes which add to unpredictability, however, can be incorporated into the system. Here the focus is given on the verification and accuracy of the CPS. Certain behaviors such as faults, failures are treated as the default behavior in a system. Anything which is away from the normal behavior of the system is known as uncertainty.

As the CPS are becoming more complex and the variation in the uncertainties are increasing at a proportional rate, it has been a part of necessity in order to analyze the system and verify it to a great extent. This analysis has become challenging to be performed via simulation. However, other methodologies that are used are mainly model checking and symbolic simulation. These two papers[5,7] discuss this approach. The correctness of a system gets affected by the increase in the uncertainties, be it either the uncertain parameter which is embedded or be the uncertain environment. Various challenges have been encountered while verifying the system, validating and classifying the uncertainties which is discussed in this paper. There are certain uncertainties that are involved in the self-modifying systems are discussed. Insufficient verification is the outcome of the integration of the components at a later stage or after the process of the verification completes. Another situation termed as inaccurate modeling occurs which is the consequence of the inaccurate devices which are modeled or other inconsistencies. The incomplete specification is another terminology which is caused due to the issues in design.

A system that is designed correctly is considered by the three various factors like validation, verification and modeling activities. In the verification process, it shows that the system is meeting certain specified properties and hence the system does the right thing. This is carried out by the process of simulation. Next, the validation is done in checking whether both the functional ad non-functional properties are meeting the expectations. Systems are created by using models at first. It gets represented by a model. As the complexity of the system enhances, there is an abstraction of the models. Therefore it is becoming more crucial for coverage. It becomes harder to predict the individual components with the increase in the complexity. Deviations caused due to the environmental changes have to be taken into account in the process of verification and validation in order to stamp the correctness of the system. In such cases, testing is required which is exhaustive testing since these complexities increase. Various factors that add to the evaluation of the correctness of the systems include the adaptive behavior of the system, unpredictable scenario handling, faults in the components, deviations that are caused due to aging. Even though researches are not enough in the fields of uncertainties; however, there are a number of cyber-physical systems that are emerging and thus, the area of uncertainties will need to study thoroughly.

Uncertainty is defined by Walker includes all forms of errors, failures, faults, unpredictable changes etc. A deterministic model can be transformed into a non-deterministic state with uncertainty. These are categorized according to the location such as the inputs, behavior of the model, the parameters. The first uncertainty which is the input, is the consequence of less knowledge or other unforeseen conditions. Uncertainties related to the parameters are caused due to the inaccuracy of the values. Like for some values, we have a range that is non-deterministic in nature. Apart from being categorized according to location, it is also classified based on modeling approach and being static or dynamic. Some of the examples of modeling uncertainties include abstraction of the models which are accurate. Examples of static uncertainties are aging, process variations whereas dynamic uncertainties include quantization error, noise etc. Uncertainties lead to error.

There are much focus and priority given to the modeling of the functionality, which is essential for validating the system. In order to proceed with the validation, two main approaches are discussed which are numerical simulation and the other is a symbolic simulation. In the case of numerical simulation, evaluation is done of a single aggregation of uncertainties. Multi-run simulation analysis is used which requires several numbers of runs in case of enhancing the coverage. However, this results in a high degree of confidence. One of them is the Monte Carlo Analysis. In this case, the statistical properties of an uncertain system are determined. Here the values are chosen in a random fashion from probabilistic models. This is in the future carried out in the repeated simulation runs. These simulation runs are directly proportional to the errors, the desired confidence. Another method is the worst-case analysis in which the performance of the system remains in some range. There are two types of uncertainties – one os deterministic uncertainty and the other is non-deterministic uncertainty. All the possible values of the discrete uncertainties are considered in case of the deterministic uncertainties. In order to find the corner cases in a systematic way Design of Experiments are used. However, there are issues with the DOE which are the detection of the border between the passing and the failing operating regions.

Even though simulation proved to be very useful, however, it cannot cover all uncertainties with sufficient coverage. Thus formal methods come into play. Symbolic simulation provides more information on the analyzed system apart from the coverage. Model-checking has been used as a part of formal specifications. Self-modifying systems have proved to be useful in modern days. Here, the behavior of the system is changed while it's still in the active state. It addresses the robustness of the system and enhances longevity. It also adds stability to the system even though the downside is the verification and the validation of the system.

It is very crucial for the cyber-physical systems to self-heal from any type of failures that come along the way. Thus the system becomes non-deterministic. Self-modifications can happen due to the following factors: Failure of components, alteration of logic which are based on unknown inputs, getting new behaviors and learning that they yield better results. Autonomous vehicles are discussed apart from self-adaptive and self-modifying systems. UAVs are controlled in a remote fashion. They require no interaction with the human. However, they are able to detect any kind of failures or other modifications or alterations to the environment. They are expected to be in a stable deterministic state when they are prone to failures in any kind. However, if there are unstable conditions, then the entire system raises a concern. The safety of a system comes first before that can be carried out for real run in the real world. For example, in the case of driverless cars, CPS is introduced in order to have control over the circumstances and environment around them. The number of uncertainties increase and so is the requirements of the systems also become robust. These uncertainties include weather-related phenomena, the failures in the component, any kind of emergency situation etc.

There are some uncertainties that are brought due to the unexpected modifications that make both the verification and validation challenging as they introduce a lot of instabilities in the system. It is expected to have the same functionality even though the system behavior and modifications happen due to the external environment and other uncertainties. The system should remain in the state of deterministic state after the verification and validation are done. Any edge cases are expected to be self-correcting. This consists of any missing data, interferences, crosstalk etc. Moden CPS is of open nature meaning adaptive behavior of the systems is the consequence of changing in the environmental inputs.

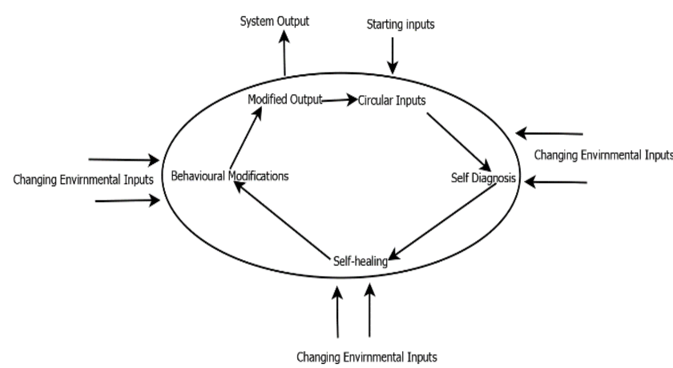

Fig 6. An open cyber-physical system with adaptive behavior

In [6], it has been noted that even though formal methods are way promising, however, there are issues with them. They are difficult to integrate into the flow of the design. Also, the scalability is way less compared to the numerical analysis. Thus it is not acceptable in the industrial domain yet.

3.1 Verification of Uncertain Cyber-Physical System:

CPS are large networked sub-systems with both physical entities and the computational entities. This nature of the CPS has both advantages and disadvantages. The flaws are that a large number of components may not have accurate values at all times and some parts might fail and might provide inaccurate sensor data. Also, resilience can be implemented which is good for the maintenance of dependable operation. CPS has found its way in aviation, in the autonomous drive of the cars. Therefore safety is mandatory before it can be implemented. Verification of the system is done in order to show that the system does not have any inherited issues and it satisfies the properties which are required. Even though the verification process does not promise any correctness of the system but it needs to be implemented. In this paper, at first, the various uncertainties are described and then its propagation and then its propagation in the various models.

In hybrid uncertainties, the uncertainties consist of continuous and discrete components. While considering the overall computation, the uncertainties of the discrete and the continuous parts are taken into account. Another motto of the verification is that no unsafe state is reached in the presence of inaccuracies, self-diagnosis. Uncertainty is inherited in the cyber-physical systems. It becomes more vital when the systems are operating in the real world. The main areas of research are on gaining the idea of uncertainty, modeling those uncertainties and finally testing them. There are three main levels of testing the uncertainties namely the application level, the infrastructure level and the integration level. In the application level testing, events arise from humans, while in case of infrastructure, they come from network equipment. While in the case of integration level, the testing arises from the interaction of the application and the infrastructure level. Knowledge is the intersection of truth and belief.

4. Extension of U-model

We consider a potential extension of the occurrence pattern of uncertainty. The U-model only considers the temporal pattern of uncertainty. However, uncertainty can be a function of spatial location as well. For example, consider a CPS consisting of a wireless sensor network. Some of these sensors can be situated in locations with more electromagnetic noise than the rest of the locations due to close proximity with communication towers or radio stations. Uncertainty can essentially be Spatio-temporal in nature. Hence we want to create another source for Pattern in the U-model: namely spatial. This only has a systematic component which could either be persistent or Spatio-temporal in nature.

We augment the pattern model inside U-model with this updated version, which would enable the U-model to handle a larger number of real-world CPS instances.

5. Conclusion:

We analyzed the two major approaches to uncertainty in cyber-physical systems in this systematic survey. The model-based approach appears more scalable and applicable to real-world problems. In this approach, UML was used to form a model of uncertainty itself and then test-modeling techniques were used to design uncertainty-aware tests. As our novel contribution to this area of research, we have added an extension to the U-model for certain specific use cases.

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