

# Access Control Challenges for Cyber-Physical Systems

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## Abstract

*With the growth of wireless networks and mobile devices, we are moving closer towards an era of cyber-physical systems (CPSs). Such systems have the potential to benefit numerous applications in areas as diverse as military, financial, and health care. However, security issues must be addressed before CPSs can be widely deployed. The problem is serious because CPSs involve interactions between a large number of entities that can span different organizational boundaries. Unlike traditional applications, these applications do not usually have well-defined security perimeters and are dynamic in nature. Moreover, these applications use knowledge of surrounding physical spaces. This requires security policies to use contextual information that, in turn, must be adequately protected from security breaches. Uncontrolled disclosure of information or unconstrained interactions among entities can lead to very serious consequences. Traditional access control policies and mechanisms rarely address these issues and are thus inadequate for CPSs. New models and mechanisms are needed to protect such applications.*

## 1. Motivation

With the growth of pervasive computing technologies, cyber-physical systems (CPSs) are becoming a reality. Such systems often use numerous, casually accessible, often invisible computing and sensor devices, that are frequently mobile or embedded in the environment and that are inter-connected to each other with wireless or wired technology. This allows CPSs to provide services and functionalities that use the knowledge of surrounding physical spaces. However, the very knowledge that allows CPSs to provide enhanced functionality can be exploited to cause security and privacy breaches. One must therefore ensure that the sensitive

resources are adequately protected from unauthorized access. Addressing this problem involves understanding what resources an entity has access to, which entities it should interact with, what information can be released to an entity, how to protect the information used or produced by an entity, which entities can be trusted and to what extent, and how these trust relationships change over time.

Consider a potential use of such technology: real-time health care for patients in assisted living. A cardiac patient lives independently in a smart home equipped with sensors and wireless controllers. The patient's movements are tracked by sensors and wireless controllers send this information to a monitoring service that oversees the patient's condition and initiates appropriate action, such as, alerting emergency services. To operate, the monitoring service needs access to the patient's medical history maintained by a health care provider. In an emergency, these records must be shared with the admitting hospital which will perform examinations, such as X-rays and ECGs. The hospital may have to consult experts unfamiliar with the patient or search for similar reports to interpret the patient's case. Security and privacy are a major concern for such applications. Preventing data transmission to the monitoring service or sending false data may be fatal. Sending too many false alarms can cripple emergency services. Disclosing the patient's health data to prospective employers may cause financial hardship and disclosing the data to unapproved doctors causes breach of privacy. Comparing a patient's report to unauthentic reports of other patients may result in incorrect diagnosis. These severe consequences motivate the need to consider security issues when designing secure cyber-physical systems.

Cyber-physical systems are different from conventional information processing systems in that they involve interactions between the cyber world and the physical world. Thus, securing such systems involve

physical security, information systems security and, most importantly, securing the interaction between the physical world and the cyber world. Security policies and mechanisms developed for traditional applications are inadequate for cyber-physical applications for several reasons. First, these applications are complex and do not have a well-defined security perimeter – the entities that a system will interact with or the resources that will be accessed are not always known in advance. This makes almost all traditional access control models unsuitable for cyber-physical systems since they base the access decisions on the successful authentication of predefined users. Second, these applications are extremely dynamic in nature – the accessing entities may change, resources requiring protection may be created or modified, and an entity’s access to resources may change while such systems are deployed. Protecting resources during application execution remains challenging. In fact, what constitutes secure operation in a dynamic environment is not yet known. Third, they use the knowledge of surrounding physical spaces to provide services. This requires security policies to use contextual information. For instance, access to a resource may be contingent upon environmental contexts, such as the location of the user and time of day. This contextual information can be used to infer the activities of the user and cause a privacy breach. Contextual information must, therefore, be protected by access control policies. Fourth, pervasive applications integrate the physical world with the cyber world. Thus, the effects of physical security must also be considered when designing access control policies. For example, if a change in environmental conditions causes the access control configuration to change, one must ensure that the sensors monitoring the environment are adequately protected. Fifth, applications in cyber-physical systems may need to interact, cooperate and share resources to accomplish a given mission. Secure interoperation in a dynamic environment is still an open problem. Last, but not least, cyber-physical systems often involve devices with various computation and communication capabilities, some of which are severely resource constrained. This will influence the access control mechanisms that can be used for such systems.

Researchers are working on various issues that may be important for cyber-physical systems. Examples include the development of new access control models and technologies [10, 13, 14, 18, 34, 35, 37, 41], formalizing the notion of trust [1, 5, 11, 12, 20, 21, 23, 26, 30, 32, 33, 38, 39, 44, 45, 47, 48], and trust management and trust negotiation strategies [3, 6, 7, 31, 40, 4, 46, 50, 51]. Some researchers [2, 8, 15, 24] have addressed security, privacy and trust issues of pervasive computing

environments and others [9, 16, 36, 49, 53] focussed on trust-based approaches for communication in sensor and ad hoc networks. Researchers have also addressed the issue of secure interoperation to some extent [17, 19, 25, 27, 28, 29, 43, 52]. However, authorization and access control, which is often the first line of defense against security breaches, has not been addressed adequately in cyber-physical systems. What is missing is an access control model for cyber-physical systems that integrates both the cyber and the physical components of such systems and allows events in the physical world to interact with and change the access control configuration. Secure operation must be defined for dynamic environments and the cyber-physical systems should adhere to them. What is also missing is a notion of secure interoperation for cyber-physical systems where different systems will interact in a dynamic environment to achieve a common mission. Access control policies should ensure that additional security breaches do not occur because of the interoperation of the various systems.

## 2. Directions for Future Research

Our preliminary research indicates that access control for cyber-physical systems depends on the following factors: (i) trustworthiness of entities, (ii) environmental context, and (iii) application context. Trustworthiness of entities play an important role in access control. This is because cyber-physical systems have no well-defined security perimeters – interactions between entities may be unknown in advance. Moreover, since many entities in cyber-physical systems belong to the physical world, there is a need to integrate the effects of physical security into access control decisions in the cyber world. The overarching theme between the two types of access control – physical and cyber – is a notion of trust. The type of interaction an entity performs with another often depends on the trust relationship between the two. In traditional access control models, the notion of trust is implicit. That is, authenticated users are fully trusted and get all the associated permissions, whereas un-authenticated users are totally untrusted and get no permission. Treating trust as a binary concept – either an entity is trusted completely or not at all severely constrains operation in cyber-physical systems. On the other hand, complete trust may not be achievable every time because an entity may have only incomplete knowledge of its counterpart. Entities will not interact with untrusted counterparts. This will often result in unavailability of systems and services. Note, however, in the physical world access decisions are frequently made on varying degrees of trust.

One research task, therefore, is to formulate an appropriate non-binary trust model suitable for a cyber-physical environment. The model must accommodate the notion of different degrees of trust, identify how to quantify and measure the trust value for the various devices and users in cyber-physical systems, and define how trust evolves in a dynamic setting. One such general trust model, proposed by Ray et al. [33], shows how trust can be represented using Jøsang's opinion model [22], describes the factors on which trust depends, and shows how to quantify the trust relationship. A lot of work, however, remains to be done before such a model can be adapted for cyber-physical applications. One area that needs further research is investigating how to compute trustworthiness of different types of entities (device, user and data) that exist in cyber-physical systems, possibly in the absence of complete information. A second area of research involves providing a formal basis that allows one to compare the different trust relationships that exist in cyber-physical systems. Since multiple entities are involved in a cyber-physical system, a third area of research needs to focus on how to compute group trust in a dynamic environment.

The next task is to identify what types of access control policies are suitable for cyber-physical systems. Although a lot of research appears in security policies, not much of this is directly applicable to cyber-physical systems. Traditional access control policies do not consider environmental contexts, such as location and time, when making access decisions. Traditional policies assume a very static configuration and the mechanisms enforcing these policies are relatively easy to implement. In cyber-physical systems, the access control requirements change when the system context is modified. Consequently, new notions of secure access control in the context of dynamic systems are needed. The security models developed for cyber-physical applications should conform to them. In short, the research task is to identify the types of policies needed in pervasive computing systems, propose models that formalize their syntax and semantics, and propose a notion of secure execution for dynamic applications.

Environmental contexts, such as location and time, play a crucial role in access decisions of cyber-physical systems. For example, a paramedic can make major medical decisions while accompanying the patient in an ambulance, but may not be allowed to do once he is admitted. Thus, access control models must take into account environmental factors before making access decisions [34, 35, 42]. Application contexts, unlike environmental contexts, are very application specific. The application context depends on the data obtained from sensors and other devices. For example, in our example

application, a patient may be hooked up to a system that continuously monitors his health. A sudden increase in the blood sugar level may trigger some action that gives an actuator permission to inject insulin to stabilize the condition. Each application context generates a specific configuration of the system. One must first define what it means for access control protection in a given application context, and also ensure that security breaches do not occur while the application context is being changed. For any given application context, the time and location of access together with the trustworthiness of the entities determine the access privileges of an user or a device. Note that, for a different application context, the privilege of this entity may change even if the other parameters (trustworthiness, location and time) remain the same. An access control model that captures all these requirements is needed for cyber-physical systems.

Different cyber-physical systems may need to interact to achieve a common mission. For example, if the smart home is on fire, the cyber-physical system of the fire department must interact with that monitoring the patient's health to accomplish the rescue mission. Under normal circumstances, these applications operate in isolation. However, in case of the rescue mission, all these applications need to interact and share resources to accomplish the goal. The issue is how to formalize the notion of secure interoperation that takes into account such ad hoc interaction among individual applications. This will require identifying the threats that can occur because of the interactions and what types of policies are needed to protect against those type of breaches. Secure interoperation requires an application to operate under different sets of policies. On one hand, the application must deal with its own policies. On the other hand, it must deal with the mission's policies. Conflicts might occur because of the interaction of different policies. Research is needed to identify how to detect and resolve conflicts. Conflict resolution should be such that it allows the mission to be accomplished without causing any security breach. Moreover, the effect of the different policies on the application must be analyzed to ensure that its execution is safe and secure.

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