The Control Technical Reference Model

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Abstract - *This paper proposes a new control technical reference model (C-TRM) using a layered architecture. Existing control architectures are focused on specific problems and do not provide for a general control communication from goal to task to execution. The upper layers of the C-TRM deal with the goal definition and validation. The lower layers address the goal to task translation and task execution. The C-TRM works closely together with the information-centric technical reference model (IC-TRM) to access information feedback at each layer.*

Keywords - Control architecture, control technical reference model, information-centric technical reference model, layered architecture

I. INTRODUCTION

A Technical Reference Model (TRM) is "a component-driven, technical framework categorizing the standards and technologies to support and enable the delivery of [reusable] service components and capabilities. [1]". The goal of a TRM is to define a standardized vocabulary describing technologies, architectures, and service components and enabling discovery, interoperability, and collaboration. A TRM is composed of service areas, service categories, and service standards. Each service area is broken down into several service categories. A category is a collection of related service standards.

Numerous TRMs have been created for numerous situations. Arguably the most widely known TRM is the International Organization for Standardization's (ISO) Open Systems Interconnection (OSI) TRM. Existing TRMs are mainly concerned with standardizing data communication and internetwork communication. The information-centric TRM (IC-TRM) [8, 9] focuses on data collection, information aggregation, and presentation, for example in autonomous smart-sensor networks, but it does not provide any control mechanism which would influence how and where the data is collected.

A variety of flavors of sensor networks is emerging out of ongoing research. While working with technology standards, such as IEEE 802.11 standards for wireless networks, each research group introduces a different information or network architecture. The control technical reference model (C-TRM) takes a generalized approach by defining a layered control architecture from a high-level goal definition to the physical task execution. Build against the IC-TRM it proposes a reference architecture in a canonical form on existing standards and suggests new standards where none exist.

In the remainder of this paper we will discuss the short comings of existing reference models and control architectures, followed by an explanation of the information-centric technical reference model (IC-TRM). We introduce the control technical reference model (C-TRM) and explain how it relates to the IC-TRM. The paper concludes with an illustrative example and outlook on future work.

II. THE OPEN SYSTEMS INTERCONNECION (OSI) REFERENCE MODEL

As early as 1978, with the growing demand for computer networks, the International Organization for Standardization (ISO) formed a subcommittee (SC16) for Open Systems Interconnection (OSI) to develop a standard for networks of heterogeneous systems [2]. In 1983 the results were published as standard ISO 7498 [3].

The ISO OSI TRM defines OSI services and OSI protocols. At the same time the OSI reference model uses a layered architecture and establishes a clear terminology in the architecture. Generally, it defines systems to be composed of subsystems or layers. Each layer consists of one or more entities with the same rank (peered). Each layer uses only the services of the layer below and provides value added services through defined service access points to the next higher layer. How the service is *performed* is not defined by the OSI Reference Model, only how the service is *provided*. The concept of a layered architecture addresses a complex problem in any number of smaller pieces (layers), where each layer can be developed and updated independently as long as it follows the defined interface protocols. In case of the OSI Reference Model, seven layers have been chosen to structure the task of Open Systems Interconnection [3, 4]. The application, presentation, session, and transport layer are host layers. They present the data in a recognizable and interpretable format. The layers below are media layers that ensure the correct delivery of the data in a timely manner. These are the network layer, data link layer and physical layer.

III. REALITY OF OSI

Day and Zimmerman state that "the OSI Reference Model cannot be implemented and it does not represent a preferred implementation approach [2]." What can be implemented are the OSI protocols. The industry implementation deviates from the OSI Reference Model: today's Internet built on Ethernet utilizes the Transport Control Protocol (TCP)/ Internet Protocol (IP). The Internet Protocol Suite or TCP/IP Suite [5] consists of a set of communication protocols (protocol stack) and roughly matches the OSI Reference Model. The shortcoming of the OSI Model in light of IP communication is its sparse lower layers in organizing IP-related protocols, while the upper layers (application, presentation, session) of the OSI Model can be combined in one application layer. The OSI layers have been reduced to three layers in the TCP/IP stack with one added Internetwork layer to capture network specific protocols such as ARP or Spanning Tree Protocol):

- *Application Layer* (OSI Layers 5-7)
- *Transport Layer* (OSI Layer 4 and 5)
- *Internetwork Layer* (OSI Layer 3)
- *Link Layer* (OSI Layer 1 and 2)

More recent technologies and protocols such as the Signaling System No. 7 Protocol [6] try to align to the OSI Reference Model, but even these protocols are – at least initially – not implementing the full OSI layer architecture.

Ongoing research derives other layered architectures from the OSI Reference Model. Alford and Varshney [7] proposed a four layer architecture for multisensor data fusion systems with a Data Acquisition Layer (on the sensor side) or a Interpretation and Resource Management Layer (on the consumer side), Connection Layer, Object Reference Layer, and a Networking Layer.

IV. INFORMATION-CENTRIC TECHNICAL REFERENCE MODEL

The same reason that drove the development of the OSI reference model sparked the proposal of an information-centric (IC) TRM by Fortier and Michel [8, 9]: data is collected and available everywhere, emerging wireless and wired sensor network technology allows for inexpensive, massive data volumes from a multitude of independent sources, and yet there has been no definition of a formal mechanism of data consolidation, association, filtering, and presentation as information.

The IC-TRM uses a six layer architecture following the conceptual layer structure of the OSI Reference Model. While the OSI Reference Model focuses on the data transmission, the IC-TRM addresses the problem of data aggregation, management, presentation, and evaluation. It represents a structured approach for transforming data into information into knowledge. The six layers of the IC-TRM are (Figure 1):

- The ***Application Layer*** presents the information in a consistent manner to the consumer. Programs for visualization or data mining are implemented in this layer.
- The ***Presentation Layer*** compares the information against external information or static references.
- The ***Aggregation Layer*** combines information from different sources relevant to a system or subsystem.
- The ***Information Layer*** associates structured information items with accurately scaled, measured data.
- The ***Data Layer*** extracts and converts all data to digital data, and verifies the correctness of the physical measurement.
- The ***Physical Layer*** collects data in unformatted, unverified, transitory format.

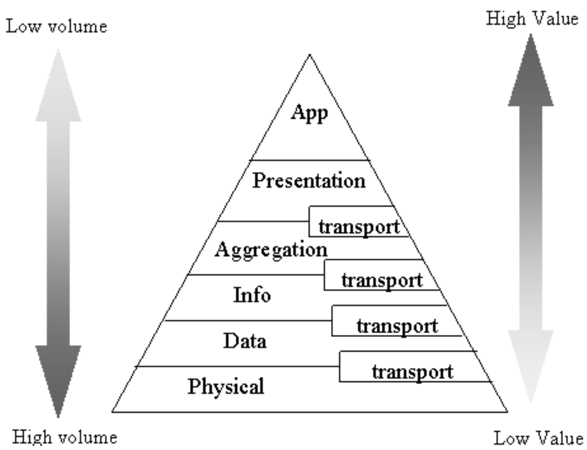

Figure 1: Layered Architecture of the IC-TRM

At the physical layer exists a high data volume with relatively low information value, whereas at the application layer the data volume is reduced significantly and the information value is very high.

The IC-TRM takes Alford and Varshney's architecture a step further. While the architecture for multi-sensor data fusion still emphasizes the system interconnection and network and maps against the OSI Reference Model, all layers of the IC-TRM are Application Layers in the OSI Reference Model using interprocess communication in a system or communication protocols such as the TCP/IP stack between IC-TRM layers. Yet both architectures, IC-TRM and the data fusion architecture, agree that the data flow is directed and asymmetric compared to the symmetric peer-to-peer communication described by the OSI Reference Model.

Rather than providing service interfaces to the next higher layer, the IC-TRM has producers (Figure 2) that extract data or information from their respective layer and insert it into the domain of the next higher layer up to the application layer. Only in the application layer (user interface) is information readily available. Therefore the next higher layer needs to provide standard interfaces to the lower level. For example: the raw data collected from sensors is pushed into the data layer as a data stream in ASCII format. Functions in the data layer transform the data into scaled measurements. The data layer producers use SQL functions to insert the verified measurements into the collection databases of the information layer.

Each higher layer provides standard interfaces for data insertion to the layer below. The producers on the lower layer must adhere to the interface standard. A layer can have multiple producers each geared towards a different data or information element. In the data layer some producers work with temperature data, while others work with humidity levels, atmospheric pressure, or air pollutants. The IC-TRM only defines what functions each layer performs, not how these functions are performed, and the interfaces between layers.

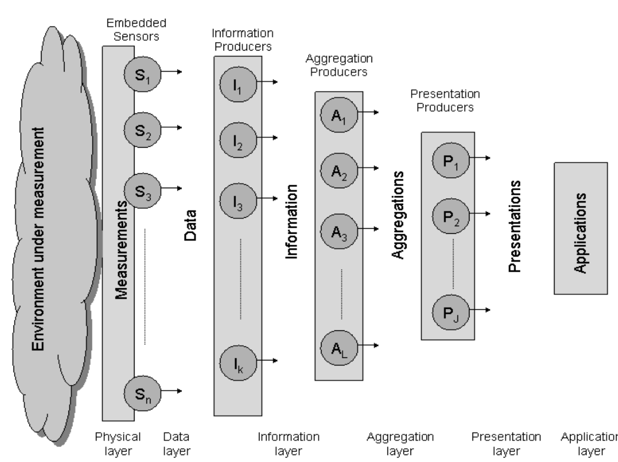

Figure 2: IC-TRM Producers

V. CONTROL ARCHITECTURES

The information-centric TRM describes the process from data aggregation to the meaningful combination and presentation of information. However, it does not provide any guidelines how this information can be acted on (moving sensors, replacing damaged sensors), or how the quality of the information can be improved (deploying more or different sensors). Applications on top of the IC-TRM may suggest to the user that "something needs to be done" or different information needs to be collected, but the IC-TRM does not specify any strategy or standard as to how an action or goal would be accomplished by breaking it into applicable tasks.

NASA and the Industrial Systems Division at National Institute of Standards and Technology (NIST) have done a significant amount of research in the area of hierarchical control. Early work focused on the theory of hierarchical control and task decomposition [10, 11], but soon evolved into the NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM) [12] with different versions of a real-time control system (RCS) architecture [13]. NASREM is a layered architecture with six layers: mission/job, task, elementary-move, key-pose, primitive layer, servo layer. In addition, each layer is partitioned in three sections - sensory processing, world modeling, and task planning – and each layer has a human operator interface.

The NASREM/RCS reference model architecture has been applied to different control problems including (multiple) autonomous land vehicles [14], (multiple) underwater vehicles [15], a sanitary landfill study [16], and automotive manufacturing [17].

The three-layered architecture for micro assembly [18] takes a simpler approach by only dividing the problem of micro assembly into a task layer, a strategy layer, and a behavior layer, but it is very specific to the problem of micro assembly. A variety of other control architectures have been introduced, for example: control architectures for mobile robots [19, 20, 21], a Web-services based remote monitoring and control architecture [22], or network related control architectures [23].

Most proposed architectures are specific to a particular problem. They all define functional blocks to structure the problem, but cannot be readily applied to another problem. The NASREM/RCS approach is a reference model but its focus is mainly on hierarchical robot control.

To this time no control architecture emerged as a technical reference model that is generic enough to accommodate the functional decomposition of a broad spectrum of problems.

VI. THE CONTROL TECHNICAL REFERENCE MODEL (C-TRM)

The proposed Control Technical Reference Model (C-TRM) addresses the problem of translating a goal into automated data collection and physical actions independent of any technology. It defines a layered control architecture (Figure 3) with six layers:

- In most cases the ***Application Layer*** is the human-computer interface and assists the user in the goal definition either visually or semantically.
- The goal is submitted to the ***Validation Layer***. This layer verifies that the goal is semantically correct and can be accomplished with the resources available to the system. Based on external data and static references the goal can be corrected or rejected.
- The ***Translation Layer*** receives the valid goal definition and breaks it into functional tasks groups. This requires knowledge about the system configuration in the lower layers. The translation layer must provide a mechanism to register low-level system components and their physical capabilities.
- The ***Distribution Layer*** refines the functional task groups into granular, task specific directives. It takes into account spatial and temporal information to determine what system components receive what directive at what time. It orchestrates the achievement of the goal.

- The ***Execution Layer*** receives the directives from the distribution layer. The directives are transformed into control signals for the physical layer. This layer implements basic error checking and safety functions in close cooperation with the physical layer.
- The ***Physical Layer*** contains sensor and mechanical functions. It is mainly hardware without added intelligence.

The upper layers in the C-TRM are goal oriented, the lower layers task oriented.

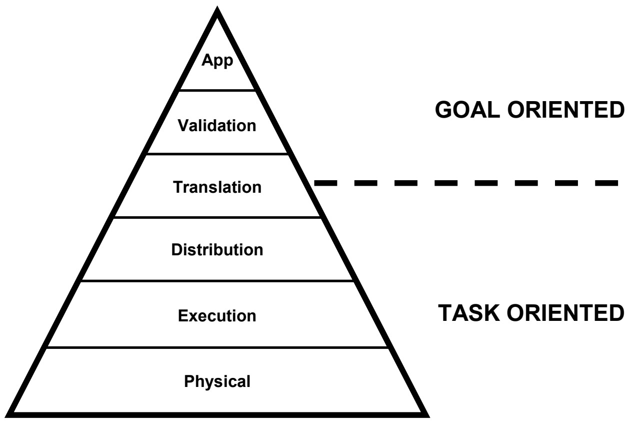

Figure 3: Layers of the Control Technical Reference Model (C-TRM)

The C-TRM alone only describes the goal to task to execution propagation. It does not contain any functionality to gather supporting data or feedback. The NASREM/RCS model [12] already showed that sensory feedback is essentially in a hierarchical control system.

The combination of the information-centric TRM (IC-TRM) and the control TRM (C-TRM) allows for exactly such feedback (Figure 4): The IC-TRM collects data and delivers information to higher levels. The layers of the C-TRM align against the layers of the IC-TRM, and at each layer the progress towards or the successful achievement of a goal can be verified. The layers that fuse the two TRMS together are the physical layer and the application layer: The same hardware platforms that collect the data ultimately execute the task directives in the physical layer. In the application layer, a user interface visualizes the information, while it provides some means of acting upon the data at the same time.

Looking back at the OSI Model, two major conceptual differences are notable:

- In the IC-TRM, the higher level does not request a service from the level below. Instead the lower level pushes data into the level above. In the C-TRM, control is mandated from the higher level to the level below.
- The information/control flows through the application layer in the IC-TRM/C-TRM combined approach, whereas in the OSI Model, the physical layer is the communication medium.

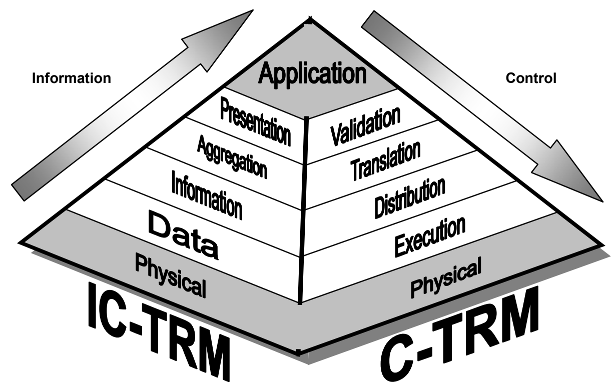

Figure 4: Combined IC-TRM and C-TRM

In order to illustrate what a real-world system implementing the IC-TRM/C-TRM architecture would look like, we consider the following scenario: An explosion in a chemical plant caused a large cloud of highly corrosive and toxic gases to form in the air. Sensors have been deployed around the disaster area. The emergency response team must monitor the toxic cloud and initiate evacuation of affected areas.

Automated, mobile sensors platforms are the *physical layer* of the IC-TRM gathering raw environment data such as toxic level, temperature, humidity, wind direction and speed, and motion or body heat caused by humans or animals. The data is communicated over a wireless network to a *data acquisition* point which verifies the correctness of the data. For example, a sudden difference in the wind speed of 50mph could indicate that the sensor was damaged and does not read correctly. The correct data is combined with sensor location and a timestamp in the *information layer*. Functions in the *aggregation layer* merge the data from chemical sensors and weather sensors based on location and time. The aggregation layer also notices when data is missing from a sensor or sensor group. The *presentation layer* accesses maps of the area, transportation infrastructure and capacities for evacuation purposes, current shelter capacities, historical weather data, and weather forecast information. All information is combined in the *application layer* in visual and statistical format. The emergency management staff then can establish evacuation routes, replace defect sensors, and relocate sensors in the predicted path of the toxic cloud with a click of the mouse.

The goal in the *application layer* of the C-TRM would be to move a group of sensors along the predicted path of the toxic cloud. The *validation layer* compares the goal against terrain maps to find a traversable path. If the terrain is obstructed by natural or manmade obstacles it would immediately reject the goal and alert the user for alternate action. The validation would also alert emergency management if there are not enough sensors available. Functions in the *translation layer* would calculate the best positions for each sensor type, for example based on GPS coordinates, proximity sensors would precede chemical sensors, and the area would be evenly covered by sensors. The *distribution layer* would implement a route planning algorithm and distribute motion and steering directives to the sensor platforms. The *executive layer* on board the sensor platforms translates the motion and steering directives into voltages applied to the motors and servos (the *physical layer* of the C-TRM).

Alternately, the translation layer could issue a control command to increase the sensor range to cover additional terrain without moving the sensor. The executive layer could implement a small NASREM/RCS architecture for basic obstacle detection and autonomous navigation.

VII. FUTURE WORK

Now that the conceptual architecture of the control technical reference model is defined, we need to take a closer look at what functions in detail each layer performs and how the layers in the C-TRM communicate with each other. Existing standards, protocols, and languages must be evaluated for use with the C-TRM or new standards defined to bridge the gaps. In addition, the interfaces to the information-centric TRM must be defined.

Once these issues have been resolved the C-TRM will build a solid foundation to design autonomous smart-sensor systems in research and industry.

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