DOMA: Deploy Once Multi Application Sensor Network Framework

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***Abstract*—Collaborating semantic wireless sensor actor network systems coupled with context driven semantic web services promise to support multiple flexible applications that were not specified before deployment. Applications range from multiple environmental monitoring tasks sharing a single network to complex systems assisting disaster response teams in developing good situation awareness and enhanced management of dynamically unfolding previously unpredictable events in a domain. Existing approaches for sensor networks suffer from a number of limitations. Assumptions of homogeneous deployments, complexity of multiple and heterogeneous deployments, narrow application specific and engineering oriented approaches have significantly limited the further development of sensor networks [2]. The authors propose a sensor actor network framework that supports flexibility through extensive semantic processing at each layer, to propel the context driven semantic web services for addressing varied mission critical applications on demand. This paper describes motivating applications, outlines the technical challenges and proposes an architecture, a methodology and implementation strategy for dynamically demanded applications. Although disaster management is used as a motivating example, the architecture is flexible and applicable for any application domain.**

I. INTRODUCTION

Flexible context driven systems integrating semantic geo sensor actor networks [4,10,11,12] and semantic web services [15] provide the infrastructure to support multiple, apriori undefined applications on demand. Unanticipated applications like disaster management cannot be precisely defined and deployed apriori. Specific tasks and actions to be performed by the critical infrastructure team members continuously evolve, as new information is available and the response task progresses. The diverse, distinct, and individualistic tasks are performed by each member of the multiple virtual teams that comprise a dynamically formed disaster response committee[9]. The success of such an operation depends on the execution of intricately balanced, time critical, synchronized sequence of diverse, distinct, continually evolving tasks and continuously supported by timely, accurate, relevant and customized information from the network.

A. MOTIVATING SCENARIOS

One motivating scenario developed by the Center for Disease Control (CDC)[7] is summarized. One evening a professional football game is being played in an outdoor stadium before an audience of 74,000. During the first quarter of the game, as a mild breeze blows from west to east, an unmarked truck passes along an elevated highway, a mile upwind of the stadium, releasing an aerosol of powdered anthrax over 30 seconds, creating an invisible, odorless anthrax cloud more than a third of a mile in breadth. The wind blows the cloud across the stadium parking lots, into and around the stadium, and onward for miles over the neighboring business and residential districts. The truck continues driving and is more than 100 miles away from the city by the time the game is finished. The anthrax release is detected by no one. After the game, spectators disperse to homes located in that state and other places in the country and abroad. Typically, symptoms start to appear in a few hours to a few days but detection of the event might take several days or months due to delays in the gathering and analysis of data. The scenario described is scary and requires us to address the issues- detection of the event, prediction of the impact area of the event, alerting other sensors to get more data, data fusion to arrive at definite conclusions on the nature of the threat and extent of the threat prediction of the area of impact and its progress, and identification of actions to be taken and warnings to be issued to target groups without any human intervention and in real time. All this is beyond the capabilities of the current sensor networks.

We envision an open network of multiple, independently deployed sensors, actors and applications assisting in the prompt diagnosis and management of disasters to transform the sensed information to a set of meaningful actions.

II. BACKGROUND

Advances in technologies coupled with miniaturization and low cost of devices has prompted the sensor network research community to promise the growth of applications at an unprecedented scale. Although applications in multiple domains have been demonstrated [16], wide spread development of sensor networks has been hampered by high deployment costs coupled with inflexible designs [8].

Limitations such as, assumptions of homogeneity in sensor hardware and software components, diversity of application requirements and objectives resulted in highly specific and inextensible designs, and the hardware limitations resulted in the inability of specific deployed applications to accommodate dynamic applications and addition of new applications over the same network [2].

The need for environments that are instrumented with sensor actor networks and which drive multiple application systems with single deployment raises the following challenge: building Deploy Once Multiple Application (DOMA) systems that scale in multiple dimensions while adhering to stringent resource constraints. The multiple dimensions include multiple modalities of components at the sensor, node, network and application levels that are dispersed over a vast spatially and temporally distributed region. Resource constraints include energy, bandwidth and processing limitations of each component. Small multi-modal sensing and acting devices with extreme energy constraints are linked to each other and to intermediate capacity nodes with low bandwidth communication channels. The intermediate capacity nodes are linked to complex computer systems and applications through higher bandwidth networks. The challenge is in the ability to achieve multi-modal spatio-temporal scale with neither overwhelming the energy constraints of the small devices nor overloading the bandwidth or processing capacities of the components in the systems and the users. To address the above challenges we propose DOMA, a novel architecture that enables context driven semantics with interacting sensor actor network and semantic web services. First DOMA facilitates deploy once multiple application system. Second DOMA is scalable in mode, space and time. Third DOMA is resource efficient.

DOMA supports multiple applications through the formation of virtual networks of hierarchy of components with varying capabilities and functionalities in a dynamic and autonomous manner. The network components could be added or removed logically and physically from the network. DOMA achieves scalability in a resource efficient manner by reducing information load at each level and in each component of the system through the generation of relevant context driven semantics. Context driven semantics is the ability to utilize semantics associated with a context to affect system behavior. Domain knowledge, and requirements and user policies, generate application level context and associated semantics that is translated to low-level parameters and which select and determine the functional and operational characteristics of each component. For instance, knowledge of human physiology would dictate range of appropriate sampling rate of biosensors, security concerns would dictate the area of coverage, and professional role of the user would dictate granularity. Similarly, sensors that are measuring phenomenon generate low-level context, and this is translated to high-level context through utilization of semantics on fused information and pattern maps, in order to detect events of interest or ignore uninteresting events. For instance, fusion of data from biosensor and environmental sensors along with knowledge of physiological effects of biological agents might trigger a terror alert event and activate relevant services to mitigate an impending disaster. Further, a detected change in sensed phenomenon may trigger a change in reporting frequency. Thus context flows in multiple directions. We define information load as the amount of information that is required to represent, transmit and process phenomenon, events and applications and this is measured or indicated by the quantity of resources needed or utilized to sense, process, communicate, receive and comprehend information. Information load could be reduced by gathering, processing and delivering only relevant information. Relevancy could be achieved through generation of appropriate context and its effective utilization through the use of associated semantics. As Pottie [16] has shown, that energy costs associated with communication are a thousand times more than those that are associated with processing, we concentrate on limiting the communication load directly or indirectly through the use of context driven semantics to decide what information is to be transmitted, what is to be processed locally, and how it is to be aggregated. Reducing communication load directly by filtering and data aggregation is common [16], but utilizing the distance semantics to distribute processing load in order to reduce communication load indirectly is a novel approach proposed in DOMA. Distance semantics is a concept that is used to minimize the function f (number of sources, intersource distance, communication bandwidth and load) utilizing the distances separating network components, their energy limitations, and bandwidths. The distance semantics provides advice processing is to be carried out locally by each network component and what is to be transmitted and to which network component.

III. PROPOSED APPROACH

DOMA provides an architectural framework that has the ability to provide customized, demanded and multiple applications based on timely, accurate, relevant multi-modal spatio-temporal information in a scalable, yet resource constrained manner.

The desiderata for DOMA systems include scalability and flexibility at multiple levels. Sensor level flexibility allows for heterogeneous sensors of varying capabilities and types to be added to or removed from the system after deployment. Scalability refers to the ability to perform acceptably well even in the face of increasing the size or functionality or both of the multi-modal sensors. For instance, a sensor network deployed to map migratory patterns, must allow the addition of GPS, body temperature, blood pressure and respiratory rate sensors at a later time to detect and contain the spread of infectious diseases. Node level flexibility refers to the ability to handle multiple message formats, multiple communication protocols, multiple priority levels, multiple resource sharing policies and multiple security concerns. A DOMA system must be scalable in spite of the increasing dimensions of operation. One application may demand extensive encoding of secure messages while another application operating in a time critical alert mode may require extremely terse messages stripped of semantic tags. Network level flexibility permits multiple semantics, multiple modes of operation, multiple fusion and routing protocols. The system must facilitate self-organizing of participating nodes into virtual networks of vary-

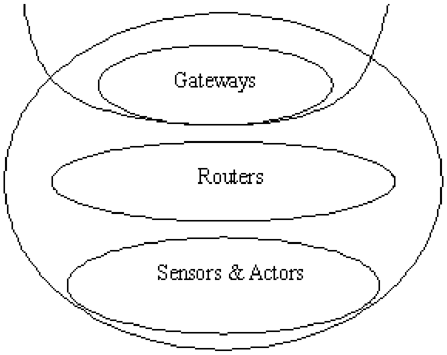

Fig. 1. Components of Sentornet:Sensor actor layer nodes forming tier 0, are small and dense with the least amount of resources, Router layer nodes forming tier 1 have more functionality, are fewer in number and perform more complex spatio-temporal fusion functions in addition to routing, the Gateway layer nodes, responsible for context generation and semantic interpretation have more powerful processing capabilities and are connected to power lines and higher bandwidth network connections.

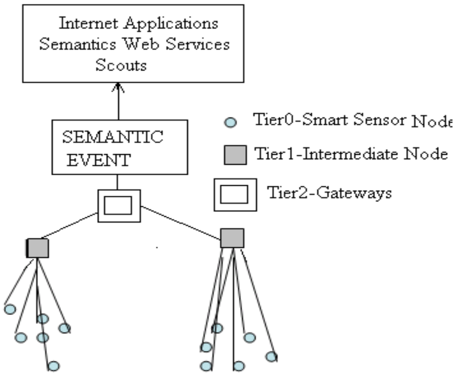

Fig. 2. Tiers of Sensor Nodes

ing sizes and shapes. Application level flexibility facilitates mechanisms for multiple application components to initiate interest; start, stop or modify operations; and collaborate with other application components. DOMA consists of a hierarchy of components with varying capabilities and limitations. The components are grouped into two major groups, the Sentornet consists of the sensor actor network and the Appcomnet is a network (internet) of application components, consisting of semantic web services, application interest registries and scouters that scout for knowledge domains, ontologies and other service components.

A. SENTORNET

The sentornet components are organized into tiers of nodes with varying densities and capabilities.

In contrast to the current architectures [16] tiered for functional abstraction to reduce cost with Tier 0 for sensing, Tier 1 for processing, Tier 2 for dissemination of data, our approach is tiered to reduce information load. The processing task is distributed across all the tiers percolating the domain semantics down and taking as much processing as possible nearer to the source to enable information load reduction at each level, distilling the information as it goes up the chain so as to enable the uppermost tier to generate an alert that is able to trigger appropriate semantic web services and applications, and deliver customized advice to the user Sensor actor layer nodes forming tier 0, are small and dense with the least amount of resources. A tier 0 node primarily performs sensing or acting and processing tasks like detecting multimodal temporal changes. These tasks are controlled by a set of initial control parameters like sampling rate, reporting frequency, alarm thresholds that were generated by application and domain context driven semantics. For instance the director of Center for Disease Control and Prevention (CDC) might issue a monitor public health query and the associated domain knowledge might dictate measuring temperature, blood pressure, heart rate and respiration of the population, which in turn translates to certain sensing modalities at appropriate sensing frequency. Communicating only significant changes reduces the information load at that level and the adjacent level. Initial control parameters also depend on user policies like security, priority and service cost. Further initial control parameters like reporting rate, sampling rate and sleep/wake times also adapt locally to the rate of change in the environment so as to conserve resources. Local processing capabilities are utilized to report a perceived pattern and its parameters as opposed to raw data to further conserve resources. Simple patterns detected at the sensor level include domain independent patterns such as constant, line or sinusoid, and domain dependent temporal multimodal fusion patterns consisting unions and exclusions that can form part of control structures established by the application and domain semantics. In contrast to existing systems where sensors are data producers with attached semantics to provide context to an application, our sensors utilize semantics generated at various levels including itself to effect behavior. Router layer nodes forming tier 1 have more functionality, are fewer in number and perform more complex spatio-temporal fusion functions in addition to routing. These nodes are capable of detecting and communicating changes and patterns across a region or the population in a region, their spread and speeds. This fused and distilled information is filtered and communicated to the higher layers as alarm messages and also to lower layers as adapting parameters facilitating dynamic auto-reconfiguration. For instance a steady state environment with several sensors in a region registering the same temperature may trigger a certain percent of the sensors to slow their sampling rate or even enter a sleep cycle to conserve energy and reduce information load. A few nodes operating in sentry mode will remain awake so as not to miss any significant events. User policies about desired accuracy, fault tolerance and operational lifetime requirements, domain knowledge semantics and current global environmental changes detected will regulate and balance the required redundancy and energy constraints. The detection of a shifting pattern like an approaching tornado will result in a change in sentry nodes to wait in anticipation of an approaching event.

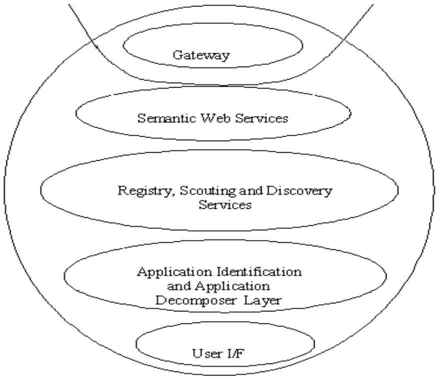

Fig. 3. Components of Appcomnet

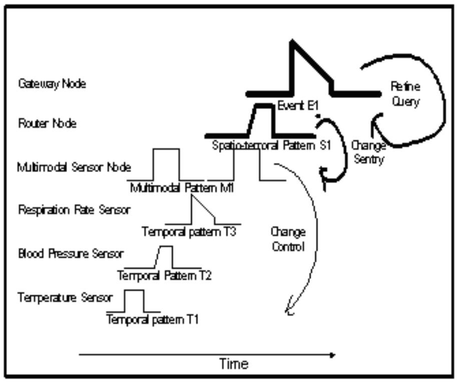

Fig. 4. Information flow during Event detection

This is an example of semantics generated at the router layer effecting behavior at the sensor layer. Just like the sensor layer, the router layer also reports patterns and their parameters. Examples of patterns at the router layer include regions and planes with parameters like modality, average and velocity. At tier 2, the Gateway layer nodes, responsible for context generation and semantic interpretation have more powerful processing capabilities and are connected to power lines and higher bandwidth network connections. These nodes forming an interface between the Sentornet and the Appcomnet use more complex pattern recognition algorithms and domain knowledge ontologies to distill information into high level alerts. An example is an algorithm that detects a significant number of respiratory abnormalities taking into account the weather conditions and climate as well as past health statistics to warrant the generation of a CDC alert. While this layer communicates with lower layers using resource sensitive protocols, it communicates with the higher layers in standard protocols that are information rich like XML, SOAP.

B. APPCOMNET

The Appcomnet, shown in fig. 3, consists of application components like gateway layer, semantic web services layer, registries and scouters and high level applications layer, Application decomposer and synthesizer layer, and user I/F layer. User I/F is responsible for taking cryptic commands from the users and deliver appropriate advices and information to the user. Gateway layer interfaces with sentornet and communicates with sentornet about the sentornet services required and takes sentornet-based data to launch apriori defined and as well undefined applications. Scouters are registries and discovery services that help applications find the right semantic web services for a particular situation. Application analyzer/synthesizer analyses or synthesizes applications. Apriori undefined applications, either triggered by the sensor data or launched by user requests, require analysis of high level tasks, decomposition into subtasks and search for semantic web services to perform the identified sub tasks.

Similarly, sensor data triggered events or user requests need to search for an already defined application that can give customized responses to appropriate users. Application decomposer/synthesizer breaks down the user commands into tasks and subtasks.

C. DOMA OPERATION

The logical components that participate in servicing an application form virtual networks functioning in registry, query or event modes to facilitate the flow of semantics to effect the operation of neighbor components.

A virtual network is a subset of system components that collaborate to provide services to an application. When a new application registers interest, a new logically distinct virtual network is formed that might be sharing physical resources with other virtual networks. Thus a DOMA system that is deployed once can be used for multiple applications. New applications that were not defined prior to deployment can be configured in novel ways using existing components. If new applications need functionalities that cannot be provided by existing components then new components can be thrown into the existing system. Thus DOMA has the ability to form small virtual networks with relevant components and functionality, determined through context driven semantics. Virtual networks offer logical simplicity at an application level and distribute complexity by sharing resources locally at component level. Through logical independence and component addition on a dynamically needed basis, virtual networks in DOMA facilitate scalable deploy-once multiple applications. Registry Mode provides a mechanism for a DOMA component to add itself into the system by advertising its capabilities and registering into appropriate registries. The sequence of actions under application registry mode and sensor component registry mode are narrated below:

Application Registry Mode

- Application registry registers high-level interests
- Scouters refine interests, define context, extract semantics, translate interests into control parameters and determine semantic web services needed to process interest.

- Refined interests and control parameters generated by context driven semantics define sentornet resources needed to process interests.
- Sentornet percolates semantics, communicates control parameter to network components, establishes resource availability and configures virtual networks.

Sensor Registry Mode

- Sensor node is added.
- Sensor node advertises its capabilities like types of measurement, sensitivity, range, multi-modal temporal fusion capabilities, and protocols used and so on.
- Neighbor sensors and routers listen and go through a sensor registry protocol to elect masters.
- Sensor becomes aware of masters and neighbors and joins the sentornet.

Sensor node waits in passive mode for application requests and virtual network formations. After going through the registry cycle, a component waits in a passive mode until its services are requested. The functional capabilities of components can be turned on or off depending on the service context generated by the user requirements as well as the sensed environment. A registered application goes through a scouting cycle to scout for knowledge necessary to refine the interest and determine resources needed to execute the interest. Subsequently the resources are polled for availability to form a virtual network. In a Query mode the context generation and semantic translation flow from the higher layers to the lower layers. An application requests specific, one time or periodic information through a high level query. The domain context and associated semantics result in the generation of specific control parameters for the lower layers. The sensors sense and report information to the higher layers that fuse and route the information to the higher layers according to the specified control parameters. DOMA component participation in event mode is shown in figure 4 and is responsible for the timely detection of events and patterns. In this mode, environmental context and semantics flow from the lower layers to the higher layers. Sensors detect and report temporal pattern to the router. As a router is connected to multiple sensing nodes, it might observe the spatio-temporal pattern of the event or phenomenon. The spatio-temporal changes may warrant a change in control parameters in ways that cannot be anticipated by the sensor layer alone. The gateway with access to spatio-temporal changes from a larger region can change the frequency or nature of the data to be acquired from the sensors, activate sensors in different regions, and generate alarms, trigger semantic web services for analyzing these alarms, and generate event triggers to applications that could deliver customized content to the users.

IV. RELATED WORK

I The design of DOMA is based on a rich literature on sensor actor networks, semantic web, web services, service-oriented architectures and distributed systems.

SONGS design [14] with a hierarchy of sensors, field servers and gateway servers using sensor ontologies offers semantic services for query type applications. The paper focuses on discussion of software architectures and programming models for gateway servers and field servers; treating sensors as simple data collection front end. Our approach considers flow of semantics in multiple directions and thus enables query type and event type applications that might not have been defined apriori. Also our framework contains mechanisms for generating not just low-level semantic events but also high-level events that trigger web service compositions for customized information delivery.

Query based applications, periodically pushing raw data streams to MySQL databases, use of ontologies to describe sensor data, building sensor web services using SOAP, WSDL and DAML-S, providing an interface to sensor data and to fuselet servers that perform data aggregation has been proposed [13]. Our approach is more flexible and scalable as semantic overhead on lower layer sentornet components is reduced through the use of compact protocols while higher layers might use high load, higher semantic standards like SOAP, WSDL, DAML-S. Semantic based routing architecture has been proposed by Juan Li, and Son Vuong[17]. However it is limited to just one functional aspect of routing while we address the information flow across all components in a more holistic fashion.

V. IMPLEMENTATION

This is description of work in progress. We have implemented some components in this framework using crossbow and Intel motes. Design work is under progress for more feature-rich and flexible motes. Work is also in progress in regard to APPCOMNET where application development on the fly using the concepts of component registry, problem recognition, problem decomposition, and application switching at the component level.

VI. FUTURE WORK AND RESEARCH CHALLENGES

This work raises a number of challenges some of which are mentioned below. Balancing autonomous flexibility and information load management: Ensuring delivery of only relevant information with the required QoS sensitivity in spite of constraints such as power, processing and communication, environmental uncertainties and hazards, balancing these functions with autonomous re-configurability, adaptability and fast switching between competing applications is challenging. Balancing the ability to react to events and to the commands, and semantic decomposition of high-level problem statements a sequence of low-level sensor tasks is a challenge. What are the best methods for measuring information load and means for comparing and evaluating the framework; what are the best ways of balancing simplicity and generality with application specific complexity; what are the best ways of measuring cost associated with distributed processing vs. centralized processing for each type of functionality are all to be addressed. Inter-sensor spatio-temporal collaboration:

Environmental issues and events of interest such as the detection of a chemical explosion, prediction of a tsunami, composing evacuation plans for hurricane victims, organizing disaster relief require coordinated actions by sensors and actors operating in multi-modal, spatio-temporal dimensions and the issues of Multimodal coordination are yet to be understood. Research challenges include strategies for coordination so as to maximize detection of true events and minimize false positives while utilizing minimum possible resources, and developing possible coordination strategies that are sensitive to the distance semantics. Systems dictating coordination messages to fall of as a measure of distance can ensure more localized autonomous processing while reducing overall network communication load. We also need to develop better adaptive protocols for sensor tasks like sampling and coverage based on local and remote semantics.Representation and Utilization of Semantics: We need to explore what are the best formalisms for the representation and utilization of semantics. We are exploring various ways of generating semantics including evaluation of a set of rules over a set of domain knowledge concepts and solution strategies for efficient generation of semantics through the use of positive and negative fuzzy rules. Application Problem Detection, Selection and Decomposition: For disaster event detection and response generation applications, it is important to recognize and select appropriate high level representations of problem events, match with associated application domains and then decompose the application problem to sub problems that can be matched with known sub-solutions which can then be composed to build new applications on the fly. This is a fertile new area with several research challenges. We are exploring this area.

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