SENSOR AND ACTUATOR NETWORKS

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2006, JANUARY

UNIVERSITY OF MACEDONIA

MASTER in INFORMATION SYSTEMS

NETWORKING TECHNOLOGIES

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ΓΚΑΡΤΖΟΝΙΚΑΣ ΕΥΑΓΓΕΛΟΣ

2006, ΙΑΝΟΥΑΡΙΟΣ

Πανεπιστήμιο Μακεδονίας

ΠΜΣ στα Πληροφοριακά Συστήματα

Τεχνολογίες Τηλεπικοινωνιών & Δικτύων

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ABSTRACT

In this project, issues concerning sensor and actuator networks are discussed. In the first part, the nature of their components is being demonstrated, together with the purpose they are trying to fulfill. Moving forward to the second part, we talk about a new approach that parallels the functions of sensors and actuators in a network with those conducted by neurons in neural systems. In the following part some research upon communication paradigms, followed by a more extensive one upon data dissemination is being presented. Moving to the end of the project, the term active rules is being proposed, followed by an outline with the most critical differences with the more traditional approach of sensor network query processors. This project is being closed with a proposition of future research challenges.

ΠΕΡΙΛΗΨΗ

Σε αυτή την εργασία, παρουσιάζονται θέματα που αφορούν τα δίκτυα αισθητήρων και ενεργοποιητών. Στο πρώτο μέρος παρουσιάζεται η φύση των συστατικών που την αποτελούν, μαζί με τον σκοπό τον οποίο προσπαθούν να επιτελέσουν. Προχωρώντας στο δεύτερο μέρος, μιλάμε για μια νέα προσέγγιση πού παραλληλίζει τη λειτουργία των αισθητήρων και των ενεργοποιητών σε ένα δίκτυο με τη λειτουργία των νεύρων στο νευρικό σύστημα. Στο επόμενο μέρος παρουσιάζεται έρευνα επάνω στα επικοινωνιακά παραδείγματα, ακολουθούμενη από πιο εκτεταμένη επάνω στη διάδοση δεδομένων. Προχωρώντας στο τέλος της εργασίας, προτείνεται ο όρος ενεργοί κανόνες, ακολουθούμενος από μια περιγραφή με τις πιο σημαντικές διαφορές με την πιο παραδοσιακή προσέγγιση των επεξεργαστών ερωτημάτων δικτύων με αισθητήρες. Η εργασία κλείνει με μια πρόταση για προκλήσεις μελλοντικής ερεύνας.

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I) INTRODUCTION

Sensor-Actuator NETworks (SANETs) are comprised of networked sensor and actuator nodes that communicate among each other using wireless links to perform distributed sensing and actuation tasks. The recent few years have witnessed an increasing interest in the potential use of SANETs in many applications ranging from healthcare to warfare. In these applications, sensors are engaged in gathering information about the physical environment, while actuators are involved in taking decisions and then performing appropriate actions in the area of interest. This enables SANETs to provide remote sensing and actuation services to their users.

SANETs are heterogeneous networks having widely differing sensor and actuator node characteristics; while sensor nodes are small, inexpensive, usually static devices with limited computation, communication and energy resources, actuator nodes are resource-rich and usually mobile. Also, the number of sensor nodes deployed may be in the order of hundreds or thousands. In contrast, actuator nodes are smaller in number due to the different coverage requirements and physical interaction methods of actuation. Typically, a deployed SANET is expected to operate autonomously in unattended environments. Operational requirements of SANETs may vary according to a network's mission defined over a multi-dimensional context, such as field of deployment (e.g., hostile versus friendly), type of application (e.g., monitoring, tracking, intrusion detection and mitigation), mode of operation (e.g., normal, exception, post-event recovery), and time. In SANETs, depending on the application, there may be a need to rapidly respond to sensor input. Moreover, so as to provide right actions, sensor data must still be valid at the time of acting.

Consequently, the issues of real-time communication and coordination are vital in SANETs. Finally, to realize their potential, dependable, secure, application-aware design and operation of SANETs have to be ensured [1].

II) A NEURAL SYSTEMS APPROACH OF SANETs.

Recent interest in wireless sensor networks has fuelled a tremendous increase in the study of signal and information processing in distributed settings. Energy conservation is very important for most interesting applications, which generally translates into minimizing the communication among sensors to preserve both individual node power and total network throughput. Consequently, much of the recent sensor network research has focused on adapting well-known signal processing algorithms to distributed settings where individual sensor nodes perform local computations to minimize the information that needs to be passed to more distant nodes.

The goal of many proposed sensor network algorithms has been to get the information out of the network (via a special node connected directly to a more traditional data network) with a good trade-off between fidelity and energy expended. However, in many applications the implicit assumption is that the information coming out of the network will be used to monitor the environment and take action when necessary. A SANET consists of a network of sensor nodes that can measure stimuli in the environment and a network of actuator nodes capable of affecting the environment. While one possible strategy summarizes information for a system outside the network to determine actuator behaviours, many advantages accrue actions are determined in-network. More subtly, sensor processing and communication strategies that blindly optimize sensor data fidelity may not yield the best results when actuation is involved.

Information strategies in the SANETs must be designed with the final actuation performance fidelity in mind.

While SANETs are often discussed, there has not been much work quantitatively analyzing their performance. Existing work can be found in areas such as software development models for SANETs [2] and heuristic algorithms for resource competition based on market models [3]. Other recent work [4] has used techniques from causal inference to evaluate specific action strategies. Most relevantly, there is also recent work [5] analyzing distributed control systems while considering the underlying communication network. A control system approach is certainly appropriate for some SANET application models. However, a control system may need more communication resources (especially from actuators to sensors) and may require the sensors and actuators to operate in the same signal space.

Merging sensed information directly into actions efficiently but without centralizing the information and decision making has rarely been considered in man-made system. Fortunately, we have examples from biology that demonstrate the effectiveness of this strategy. Neural systems perform a chain of tasks very similar to the needs of SANETs: sensing, analysis and response. Furthermore, evidence indicates that neural systems represent and process information in a distributed way (using groups of neurons) rather than centralizing the information and decision making in one single location. This shrewd strategy avoids creating a single point of system failure and allows the system to continue functioning in the presence of isolated failures.

In neural systems, two types of behaviours exist, depending on whether there is "thinking" involved, which we call conscious and reflex behaviours. In conscious behaviour, biological systems gather sensory information, make inferences from that information about the structure of their environment, and generate actions based on that inferred structure. In reflex behaviour, a sensed stimulus directly generates an involuntary and stereotyped action in the peripheral nervous system before the brain is even aware of the stimulus [6]. An example of a reflex behaviour is the knee-jerk reaction achieved by a doctor's well-placed tap below the kneecap. A more subtle example is the eye position correction that allows our vision to stay focused on an object even when our head is moving.

SANET applications have an analogous division, which is called object-based and measurement-based network tasks [7]. For example, the canonical target tracking scenario is an object-based task because it involves using sensory measurements to infer information about objects in the environment. On the other hand, an application such as agricultural irrigation is a measurement-based task because sensor measurements directly contain all the necessary information – there is no underlying environment object to try and infer.

III) COMMUNICATION PARADIGMS AND DATA DISSEMINATION IN SANETs

In the last couple of years, sensor network research, has addressed the development of sensor platforms[11],application domains, and algorithms. Because sensor networks depend on multiple nodes cooperating with each other, an effective communication paradigm is of prime importance and has been researched upon[9][12][15][16].

Noteworthy communication paradigms are: (i) Directed Diffusion[12], a general purpose, network oriented approach to data-centric communication in sensor networks (ii) IDSQ[15], an information oriented approach that combines data routing with information optimization objectives, and (iii) TAG[16], a database oriented approach to address numerous sensors in aggregate by means of SQL queries and gather the data back to a single, central server.

Today's Internet combines different devices such as routers, servers and hosts, even the routers can be classified into different categories (e.g., into core routers and edge routers).Large scale sensor networks may have thousands of nodes in the future. It is more realistic to have hierarchical models of network devices rather than flat ones.

Previously proposed data routing protocols for sensor networks have not been designed to leverage the capabilities of hybrid devices by exploiting resource rich-devices to reduce the communication burden on smaller, energy, bandwidth, memory and computation-constrained sensor devices. Consequently, they may not be best suited for hybrid sensor network applications involving several mutually cooperative sinks.

In the following section, I will cover some research in data dissemination.

Directed Diffusion: Directed Diffusion [12] is a data-centric, reverse-path based communication paradigm for sensor networks. Sinks flood their interests into the network when they join the network. An interest is a query specifying the attributes of the information a sink wants a sensor to collect and respond. Sources in turn flood the first few exploratory data pockets into the network. Sinks select and reinforce the best paths and the sources use reverse best paths to deliver data back to the sinks.

TTDT: Two-tier Data Dissemination mechanism [9] tries to set up a virtual grid by calculating the distance between sensors and relaying spots. The sensor with minimum distance becomes a relaying point. The sources broadcast their query/interest within the grid and the query/interests are forwarded by the relaying sensors to the sources.

The sources transfer the data packets along the reverse path to the sinks. Compared to Direct Diffusion, it can better handle sink mobility because the query/interest is limited in one local grid. However, it may still introduce replicate data packets transmission to multiple sinks.

Manycast: Manycast [8] is a recently proposed group communication scheme for ad hoc networks. However manycast allows a source to communicate with many destinations simoultaneously.

Internet anycast: The Internet community has addressed anycast reaserch extensively [10][13]. However, the environment is radically more dynamic in sensor networks and sensor nodes have significantly limited resources.

Multi-robot coordination: Within the field of distributed mobile robotics, Daniela Rus et al [14] have addressed the problem of maintaining continuous communication to route data among mobile robots.

Tree-based anycast [17]:In this case we have a hybrid sensor network consisting of both resource-rich micro-server nodes and low-power sensor nodes. There are also multiple microservers interested in the same data. Sinks could be mobile. Data needs to only reach one sink, thus motivating an anycast service. Sensor network applications can handle small amounts of data loss and therefore anycast does not need to explicitly provide reliable data delivery. A straight-forward approach to implement anycast is using an expanding-rich search with feedback from micro-servers. This is attractive because it is self-organizing and robust, requires minimal network state and can limit the flooding scope in diffusion. On the other hand it is not well suited to handle sink mobility. It incurs high latency and energy overhead if a sink leaves because it must discover a route to an alternate nearby sink. Moreover, it may require sinks to synchronize with each other before sending feedback to the event source. Instead, a shared tree approach can be adopted. Corresponding to each event source, a shortest-path tree rooted at the source is constructed. Sinks form the leaves of the tree. Sinks can dynamically join or leave the anycast tree. Although this approach requires more network state, it is a good approach to handling mobility, as it simultaneously maintains paths to all sinks. By eliminating the need to discover paths to alternate sinks each time a sink leaves, it can reduce worst-case latency and does not require synchronization among sinks.

Simulations [17] have shown that anycast service when added to Directed Diffusion can: (i) significantly reduce end-to-end latency (ii) significantly reduce energy consumption (iii) balance network load more evenly by forwarding data traffic locally rather than globally and (iv) handle low to moderate sink mobility with minimal extensions (as evidenced by the high data delivery rates achieved) but may require further modifications to handle higher mobility rates. While radio links work very well in simulation they can be notoriously lossy in practice. These results need to be further validated experimentally.

IV) ACTIVE RULES IN SANETs

Application development for sensor and actuator networks presents unique challenges since it has to address the complexities of distributed and often decentralized operation, the highly resource constrained nature of network nodes and the highly transient nature of network topology [19]. Moreover, applications must operate unattended for prolonged periods of time and still maintain their integrity and quality of service.

In recent years it has become clear that the investigation of higher level computational paradigms is necessary so as to abstract the complexity of systems development and offer application developers with a more amenable programming framework. To this end, query processing has attracted considerable interest and is rapidly becoming a popular computational paradigm for a plethora of sensor network applications. This approach has been seen to address well the complex requirements of application development in sensor networks in a variety of applications including environmental monitoring, distributed mapping and vehicle tracking [20, 25]. Prototype sensor network query processors have been implemented in Tiny DB [24] and Cougar [27] systems. Another database technology that may provide an appropriate computational model for a distinct set of sensor and actuator network applications is event-condition- action (ECA) rules [26]. Indeed, sensor and actuator network applications often operate in one of either modes:

(i) In event-driven applications, for example detection of forest fires, security management or product detection in ubiquitous retailing [23], the system remains inactive until an event is generated in one of the nodes, then the event propagates through the system which subsequently initiates appropriate actions in response to this event,

(ii) In demand-driven applications, for example environmental monitoring [20], activity is initiated in response to external requests, usually in the form of queries.

While query processing matches well the characteristics of the later class of applications, an ECA rule-based approach offers a better fit for applications with execution profile that corresponds to the first pattern above. In such applications, the system needs to provide a timely response to events and although in principle this would still be possible using a sensor network query processor, its deployment would unnecessarily consume the limited resources by regularly checking for events that may not have occurred.

Moreover, ECA rules can provide a natural computational paradigm to sensor and actuator network applications that require reactive behaviour [28][48]. While sensor network query processors (SNQP) [18, 20, 24] have proven very successful in providing appropriate abstractions for user interaction, ECA rules address the problem of unattended system behaviour and can effectively model application logic in autonomic situations. In the context of such applications the system is required to provide a timely response to events at the lowest communications and computational cost. Although potentially a SNQP could be used for this type of application, in practise it would unnecessarily consume limited resources by regularly checking for events that may not have occurred. Indeed, SNQPs primarily address data acquisition from a relatively small number of vantage points. ECA rules may provide an effective and efficient mechanism to support reactive behaviour by localizing control and by providing a mechanism to react to events rather than proactively test whether a particular event has occurred.

This difference in scope between SNQP and ECA rules implies that the two systems have vary different execution profiles which also means that they also have very different requirements. In the following paragraphs it is attempted to outline the most critical differences between the two approaches [28][48].

(a) Vantage Points. SNQPs assume that queries are initiated at a single or a relatively small number of vantage points, with data aggregation potentially carried out at a few intermediate locations, the so-called storage points. In ECA rules at any sensor in the network may generate an event which may be used by any actuator also potentially placed at any network location. Thus, an ECA rule may fire at any node location within the network and may also activate any node within the network.

(b) **Communication Pattern. SNQPs collect data in regular patterns which sensor nodes can use to synchronize and agree on wake-up/sleep cycles. ECA rules are reactive and thus rules fire at unpredictable, irregular intervals. Hence, wake-up/sleep schemes that can support this asynchronous mode of operations are required. Moreover, this irregular pattern implies that nodes consume power at different rates and for this reason node failure is more irregular and harder to predict.**

(c) **Routing. SNQPs currently mostly use tree-based routing mechanisms that flood the network at least once, during the tree construction stage. In this context the communications overhead placed by the route discovery stage is justified by the relatively large amount of data that is being collected. An ECA rule processor is characterized by small, incremental updates rather than a single data collection step and thus the route discovery stage of tree-based algorithms would dominate the communications cost. Consequently, globally optimal routes would probably not optimize power consumption for the network as a whole and localized routing algorithms could be more efficient [22].**

(d) Data Model. SNQPs currently view the sensor network as a single data space. ECA rules require an alternative data model which distinguishes between the different types of objects that are being observed and generate events.

(e) **Aggregation. Aggregation in ECA is carried out at the signal rather than the query layer which is the norm for SNQP. Although the mathematical techniques used for aggregation in SNQP [21] can also be used in ECA rule processing, this is done at a lower layer and within a** particular topic channel in an approach akin to collaborative signal processing in distributed environments.

(f) In-network storage. Although both systems clearly benefit from in-network storage, SNQPs develops hierarchical-directional mechanisms based on the tree-based routing algorithms employed, whereas ECA rules benefit from decentralized-flat and schemes at the topic channel level.

(g) Network Segmentation. ECA rules execute within a specific network locality and thus can be relatively resistant to network segmentation for example due to loss of connectivity caused by intermediate node failure. ECA rules may still fire despite their isolation from a sink controller.

V). RESEARCH CHALLENGES

A. Sensor-actuator coordination

In SANETs, multiple actuators can receive the information from sensors about the sensed phenomenon and this case is denoted as Multi-Actuator (MA). Unlike this situation where sensor readings are sent to multiple actuators, only one actuator receives event features, this case is denoted as Single-Actuator (SA). In fact, SA can be considered as a special case of MA. The following research issues related to SA and MA cases can be concluded for sensor-actuator coordination in SANETs

[32]:

- To ensure that there are no adverse effects on the target environment.
- To ensure synchronization in the reporting time of the sensed phenomena between different actuators.
- In MA, it is necessary to send the information only to a subset of actuators which cover the entire event region.

- The advantages and disadvantages of both SA and MA need to be analytically investigated to figure out which one is appropriate for given applications or situations.

B. Coordination among actuators

In SANETs, actuators communicate with each other in addition to communicating with sensors. Actuators coordinate explicitly and with purpose either in centralized way or in distributed way in order to solve the task assignment problems in SANETs. This coordination has the following challenges [32]:

- In a single-actuator task case, the problem is how to select the single actuator among all capable actuators and how to find an optimum number of actuators performing the actions in a multi-actuator task case.
- A communication model between actuators.
- Execution of different events detected in a region may be required to ensure that there are no adverse effects on the target environment.
- Some applications may require synchronization of actuators to act on the event at the same time.
- There is a need to specify the contents of messages and algorithms which provide efficient data transmission for different types of messages.
- How to select an actuator which will function as a decision unit.
- Coordination and communication protocols should support real-time properties of SANETs.

C. Transport layer

The new transport protocols must support real-time requirements in SANETs. Several transport layer protocols have been developed for ad-hoc networks and wireless sensor networks in recent years [29][33] [34]. However, there exist no transport protocols which deal with both the reliability and real-time for SANETs to date. Since sensor-actuator and actuator–actuator communications occur consecutively in SANETs, a unified transport protocol is required for both cases.

D. Routing layer

In SANETs, when sensors detect an event, there is no specific actuator to which a message will be sent. This uncertainty occurring due to the existence of multiple actuators causes challenges in terms of routing solutions. Selecting an actuator node is one of the challenges for a source sensor node. In addition to determining the path selection and data delivery, routing protocol should support real-time communication by considering different deadlines due to different validity intervals. Moreover, the routing protocol should also consider the issue of prioritization and should provide data with low delay bounds to reach the actuator on time.

In recent years there has been a considerable amount of research on routing problems in sensor networks [30]. An anycast mechanism developed in [31] does not support the sensor-sensor coordination occurring in SANETs due to the result of correlated information among multiple sensor sources which detect the same event. Moreover, this mechanism causes a sensor which is one hop away from an actuator to receive also interests from an actuator on the other side of the network. This may cause unnecessary traffic load in the network. SEAD developed in [35] is also not suitable for SANETs since it does not deal with end-to-end delay minimization which is one of the main goals in SANETs. Furthermore, it is developed for the case where all sinks request data from one source at refresh rates, whereas in SANETs only actuators which are in the vicinity of a phenomenon are interested in the event information. SPEED [36] is an adaptive, location-based real-time routing protocol which can be effectively used if the location information is available in all sensor nodes and the location updates can be delivered to the source

sensors regularly. However, SPEED is not suitable for SANETs since it does not support Multi-Actuator (MA) case and the mobility of actuators.

Moreover, a model with resource-limited sensor nodes and higher energy capacity cluster heads is given in [37]. This model may be suitable for SANETs such as an actuator can become a cluster head and each source sensor can become a member of a cluster. However, several open research issues must be investigated such as

- How are the clusters formed, e.g., are they formed based on the event?

- How will the clusters be adaptive to mobility, or

- How will the clusters satisfy the real-time constraints? For actuator–actuator communication, routing protocols developed for ad-hoc networks such as DSR, AODV, OLSR [38] can be used as long as they are improved so that real-time requirements are met and communication overhead occurring at sensor nodes due to actuator–actuator communication is low.

E. Medium access control

In order to effectively transmit the event information from large number of sensors to actuators there is a need for MAC protocol. Moreover, in some applications, (i.e., distributed robotics) actuators may be mobile. As they move, they may leave the transmission regions of some sensors and enter other sensors region or they may become totally disconnected from the network. Therefore, another function of MAC protocol in SANETs is to maintain network connectivity between sensors and mobile actuators. Furthermore, as discussed before, the timely detection, processing, and delivery of information are indispensable requirements in a sensor/actuator network application. Classical contention-based protocols are not appropriate for real-time sensor-actuator communication since

contention-based channel access requires handshaking which increases the latency of the data. TRACE [39] is a reservation TDMA protocol which suffers from the added overhead for reservation contention while PBP (Predictive Backoff Protocol for IEEE 802.11) suffers from the requirement of large amount of energy due to all sensors listening to others transmissions.

By exploiting the periodic nature of the sensor network traffic, a collision-free real-time scheduling algorithm is presented in [40]. Collision-free protocols may be suitable for SANETs, because they can potentially reduce the delay and provide real-time guarantees as well as save power by eliminating collisions. A problem in a large class of current collision-free protocols is the use of multiple channels [40].

This imposes a nontrivial requirement on the hardware of the nodes in the network as mentioned in [41]. Thus, further study is needed to tell whether the performance gain would overcome the increased cost of the hardware. Moreover, in [40] and generally in all existing collision-free protocols the mobility is not investigated. For actuator–actuator communication, the existing MAC protocols developed for ad-hoc networks cannot be directly used. They should be improved so that they support real-time traffic, since in SANETs, depending on the application, interaction with the world may impose a real-time constraint on computation and communication.

F. Cross-layering

Current WSN and WSAN protocol designs are largely based on a layered approach. However, the sub-optimality and inflexibility of this paradigm result in poor performance for SANETs, due to constraints of low energy consumption and low latency. Therefore, instead of having individual layers, there will be a need of cross-layering where layers are integrated with each other.

G. Products development

There is a large amount of work on developing microelectromechanical sensors and new communication devices. The development of these new devices make a strong case for the development of a software platform to support and connect them. TinyOS is designed to fill this role [42]. Current real-time operating systems do not meet the needs of the emerging integrated regime. Many of them have followed the performance growth of the wallet size device. Traditional real time embedded operating systems include VxWorks, WinCE, PalmOS, and QNX and many others. A major architectural question in the design of network sensors is whether or not individual microcontrollers should be used to manage each I/O device. It is possible to maintain multiple flows of data with a single microcontroller. This shows that it is an architectural option - not a requirement - to utilize individual microcontrollers per device. Moreover, the interconnect of such a system will need to support an efficient event based communication model. Tradeoffs quickly arise between power consumption, speed of off chip communication, flexibility and functionality [42][43].

Though there has been much work in developing and deploying embedded control systems that use wired sensor and actuators, using low-power wireless sensor-actuator networks fundamentally changes the nature of the problem because of the bandwidth and power limitations of these networks. Wireless sensor networks themselves have been a very active area of research in recent years, but most of this work has focused on the sensing aspect of WSNs, and not as much on actuation [44]. Moreover, sensor networks have been successfully deployed for passively monitoring environments, but there has been relatively little work towards developing networks that make changes to the environment [45][46]. Not to mention that there is a small amount of work studying the effect of dropouts on the performance of networked control systems. Nearly all of this work has confined its attention to single control loops, rather than the multiple coupled control loops [47]. Finally, SANETs can provide the ability to continuously monitor the integrity of structures in real-time [50], detect damage at an early stage, and provide robustness in the case of catastrophic failures with a fraction of cost associated with today's wired networks. However, SANETs require a new paradigm of computing-one which explicitly addresses less capable hardware, unreliable communication with limited bandwidth and severe energy constraints [49].

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