Special issue on International Workshop on Networked Sensing System

Trans. of the Society of Instrument and Control Engineers
Vol.E-S-1, No.1, 52/57 (2006)

Prototype of a Sensor Network with Moving Nodes[†]

Ryohei Suzuki [*], Kazunori Makimura [*],
Hiroki Saito [**] and Yoshito Tobe [**]

Because of the progress of the robotics and mobile ad hoc networks (MANETs), we can expect that networked robots are utilized in a variety of fields including sensor networks. However, literature in sensor networks are dedicated toward problems related to static network. In these backgrounds, we present a basic architecture and its protocols for sensor networks with mobile nodes. In our system, we have three significant aspects: First, we have classified behaviors of nodes into multiple modes. Second, a node can instruct other nodes to move to a specified position if desired. Third, a node decides its action without any assistance from an administrator or any centralized infrastructure. In this paper, we describe a prototype of our architecture and discuss it.

Key Words: mobile sensor networks, self-organized networks, mobile ad hoc networks, networked robotics

1. Introduction

Over the past few years, MEMS-based sensor technology have enabled the development of relatively low-cost and low-power wireless sensors (WSNs). They can be used in many scenarios such as environment monitoring, failure detection, intrusion detection, etc. Since the notion of wireless sensor networks was proposed 6) etc., many issues regarding sensor networks such as data dissemination, aggregation, and management of their database have been investigated. In many cases, the number of sensor nodes is assumed to be large to enhance coverage and robustness of the network. They need to be deployed in a wide area such as a national forest, a large park, and a huge farm. In addition, they need to be redundant to allow failure of several nodes. The key feature in the deployment of such many sensor nodes is static placement of the nodes. Once a node is configured into a sensor network, its location will not change.

Besides the advances in these network and sensor technologies, we have seen a rapid progress of robotics. Multiple robots can constitute distributed autonomous robotic systems (DARS) 1). These robots can carry sensors, thereby facilitating creation of mobile sensor networks utilizing robots. In contrast to deployment of sensor nodes to a wide area, such a mobile sensor network requires several tens of nodes. However, the coverage and robustness can be enhanced by the nature of mobility to necessary locations.

In these backgrounds, we define mobile object networks (MONETs) that consist of intelligent mobile robots collaborating to achieve some assigned tasks. In this paper we present a prototype of MONET called Routing Assisted by Moving objects (RAMOS). We also show a result of a prototype of RAMOS and discuss its direction.

In the following, section 2 gives design of RAMOS system. Section 3 describes a prototype system. Section 4 presents related works of RAMOS. Section 5 describes future work and Section 6 concludes this paper.

2. System Architecture

In this section we describe assumptions about RAMOS and its system architecture. RAMOS is a multi-hop sensor network including mobile nodes. Data forwarding in RAMOS is based on on-demand, hop-by-hop routing protocol assisted by physical movement of other nodes in the network. A forwarding node normally sends packets to immediate neighbor according to next hop information in its routing table.

2.1 Assumptions

We assume that all nodes can identify their locations. Mobile nodes need location information for their routing. Therefore, identification of locations is necessary in RAMOS. MICA2 Motes 13), used for our prototype, can optionally accommodate GPS devices 14). Although nodes can obtain their location using GPS devices outdoors or

---

[†] Presented at INSS2004 (2004.6)

[*] Graduate School of Information Systems and Multimedia Design, Tokyo Denki University, Chiyoda-ku, Tokyo

[**] Department of Information System and Multimedia Design, Tokyo Denki University, Chiyoda-ku, Tokyo

(Received November 14, 2004)
(Revised July 30, 2005)

ultrasonic-based positioning systems indoors, we do not confine ourselves to positioning with high resolution. In some cases, rough positioning is sufficient with regard to a wireless communication range of a node. Based on the above assumption, destinations of data can be specified with location of receiving nodes. RAMOS has the following features :

- Data forwarding by either physical movement of nodes or wireless communication.
- Ability of instructing other nodes to a specified position to assist data forwarding.
- Mode classification depending on ability of movement.

These features exploit a combination of wireless communication and physical movement in order to discover next-hop nodes and convey data to final destinations. Each node decides its action by itself without any assistance from an administrator or any centralized infrastructure; actions of nodes are determined in a distributed manner.

Since the destination of a receiver is specified with its location, an intermediate node that has received data can determine if there is a neighbor node that is nearer to the destination. The intermediate node first looks up such neighbor nodes by broadcasting neighbor-discovery-request message. The node chooses the next hop node by received replies from other nodes. If there is no appropriate next hop node, the node itself moves towards the destination.

2. 2 Classification of Modes

Node movement in RAMOS framework depends on location information, types of message and multiple modes, i.e., absolutely static (AS), semi-static (SS).

Nodes in AS mode stay at their original positions and do not move to serve as backbone routers of the network for the duration of their lifetimes. SS nodes behave like AS nodes except that they will move when urgent event occurs. SS nodes always return to their original locations after their journeys in order to stand by for the next incoming event. At the inital stage of depleyment, mobile nodes are placed onto a certain point and start to move. The positions of AS and SS nodes are pre-determined before they are deployed. Furthermore we are considering other modes in order to achieve a more efficient network: dynamic search (DS), limited search (LS), spontaneously moving (SM), and round patrol (RP) mode. DS nodes can freely move anywhere at any time whenever necessary. Nodes in LS mode move within limited areas (i.e. their radio coverage) to search for assistants. SM nodes randomly move around the network until they change to other modes. A node in RP mode is an assistant of an AS or an SS node and if it serves as an assistant for many nodes it patrols for such nodes.

We attempt to optimize a network by using these mode and local decision. However the more we consider the many modes, the more complicated a network is. Therefore, to formalize the problem simple, we focus on a simplest network which consists of AS and SS nodes. We then discuss its results for more complex one. The followings are behaviors of AS and SS nodes.

AS Mode: AS nodes do not move at anytime, and behave as a backbone router; an AS node forwards a request to the next hop if it exists, otherwise it waits for assistance from any incoming other nodes. If it finds the assistant node, it forwards the data to its assistant.

SS Mode: SS nodes behave like AS nodes except that they will move when urgent event occurs. Thus an SS node forwards highly urgent request to its neighbor node other than AS nodes. If there is no such a node, it moves to the destination of the request directly. Otherwise, the SS node passes the request to a discovered assisting node and returns to its original location. Upon receiving a low urgent route request, an SS node forwards the request to its neighbor node other than AS nodes. If the SS node has no such immediate neighbor, it waits for T_{patrol} seconds for an incoming node. If it does not have its own RP node yet or T_{patrol} has expired, it starts to search for an assistant within a limited area. In an extreme case, if the SS node does not discover any node, it goes back to its original position and waits for an incoming node.

3. Prototype

In this section, we describe a prototype system of RAMOS. In order to formalize the problem simple and discuss its results for more complex one, we focus on a simplest network which consists of AS and SS nodes. The followings are our methodology and results.

3. 1 Methodology

We consider a prototype network which consists only of AS and SS nodes. To observe this simplest situation, we have constructed a prototype system consisting of one static and two mobile sensor nodes on 5-m one dimention area. Both of nodes are equipped with MICA2 Motes. Lego MindStorm RCX2s (12) are used to carry MICA2

Motes for the mobile nodes. **Fig. 1**, **Fig. 2** and **Fig. 3** show the prototype system. In the Fig. 2 and Fig. 3, E1 and E2 stand for event-generators. The event-generator generates a highly urgent event message with specified destination at random time. PC1 and PC2 are personal computers to control mobile nodes via IrDA. M1, M2 and M3 stand for mobile nodes. M1 and M2 are SS mode which can move to a specified destination if it required. Distances between each node are 2.5 *m*. Communication range between any two nodes is set to 30 *cm*. M1 and M2 move to a destination when they receive an event-message from event-generator. RCX2 then detects their positions by reading sensed value of brightness of reflected light from the floor. A speed of both M1 and M2 is fixed at all time in our prototype. This is because we attempt to observe a result of using modes.

There is one limitation, motes on the mobile nodes cannot instruct them to move directly; CPU of a Mote cannot communicate with CPU of an RCX2. To overcome this lack of communication, MICA2 Mote sends an instruction of movement to a static node. The instruction is forwarded to the controlling PC1 and PC2, and control mobile nodes via IrDA.

A state transition diagram of an SS-mode node is shown in **Fig. 4**. When a node receives a message, it determines the message type. When it receives a Query-Request message which is used to search for a next-hop node, it sends a Query-Reply message with its location information. By receiving the Query-Reply message, the corresponding node decides to send a Move-Request message depending on the location information. If its location is nearest to the destination, the corresponding node sends an Abort message to discontinue the instruction. In general, the Query-Reply messages come from multiple nodes. In such a case, the node which is nearest to the destination is able to become the next-hop node. The node which received a Move-Request message moves to the destination, and after the journey it returns to its original position.

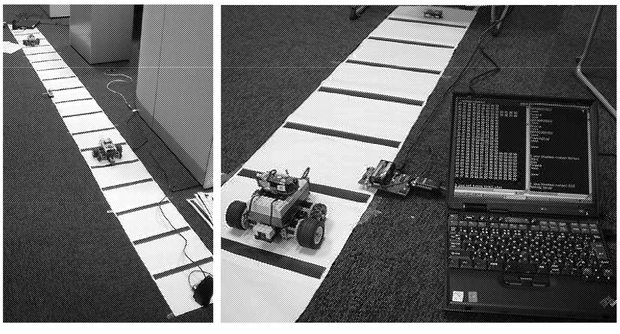


Fig. 1 Testbed

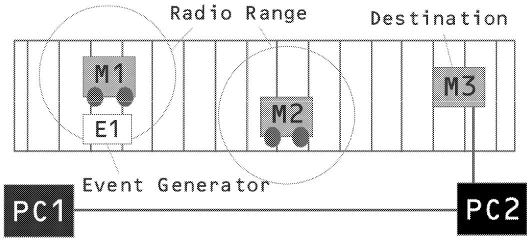


Fig. 2 Case 1

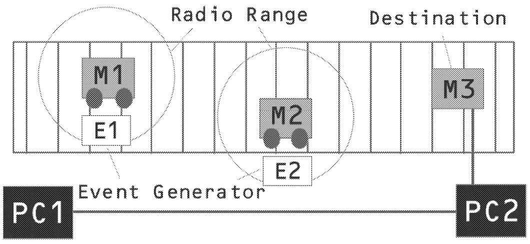


Fig. 3 Case 2

In the prototype of RAMOS, we conducted the following two simple cases:

Case 1: Only E1 generates event-message which destination is M3 at random time.

Case 2: Both E1 and E2 generate event-message which destination is M3 at random time.

We considered the following two types of node behaviors at each case: RAMOS and Non-RAMOS. In a case of Non-RAMOS, a mobile node cannot instruct any other nodes if it finds them in its journey to the destination. In both case 1 and case 2, an event-generator generates highlu urgent event-messages at random time. Under these conditions, we measured 10 times at 5 different generation rates at each case.

3. 2 Evaluation and Discussion

In this section, we present the evaluation of our prototype and discuss it to improve a network performance.

Figure 5 shows the effect of offered load on every event generation rate in case 1. RAMOS works at higher delivery rate than Non-RAMOS. This is because M1 uses a whole resource of M2 in RAMOS whereas M1 does not use the resource of M2 in Non-RAMOS. However it is important that the delivery rate in RAMOS is more than two times than the one of Non-RAMOS.

Figure 6 shows the effect of offered load on every event generation rate in case 1. RAMOS works still at higher delivery rate than Non-RAMOS. In this case, resources at both RAMOS and Non-RAMOS are suppose to be same amount, and it is because of this that the delivery rate is

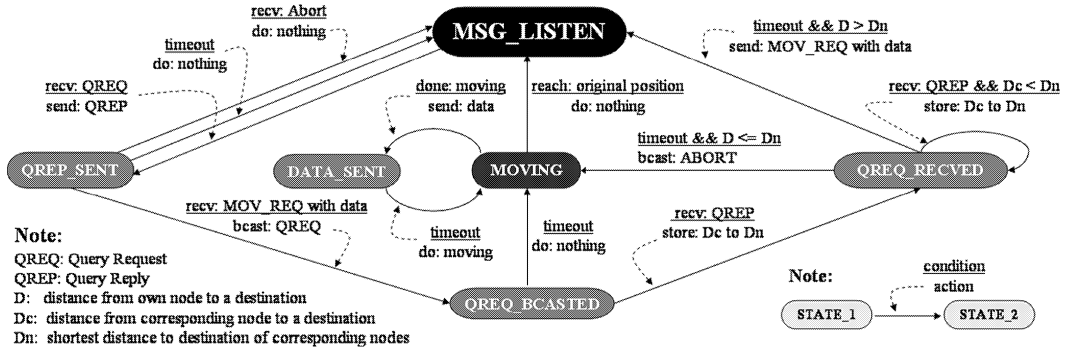


Fig. 4 State transition diagram of an SS node

more close to each other than case 1.

As you see in the Fig. 5 and Fig. 6, RAMOS has higher event delivery rate than non-RAMOS. This is because SS nodes help other nodes if the event is highly urgent. This means that the classification of modes make the rescues increase temporally. Otherwise, for a low urgent events, an SS node does not move to a destination to prevent an energy consumption though the event delivery rate is decrease than for highly urgent event. We leave an evaluation of energy consumption as a topic of future works.

As the event generation rate increases from 0.34 events per second at each case, the event delivery rate keeps low percentage. In order to overcome this issue, we are considering increasing a network resource temporally by changing modes of node. Compare to case 1 and case 2, we suppose that increasing a local resource temporary is the key of improving an event delivery rate. SM and DS nodes which we describe at previous section are supposed to improve temporary by helping other AS and SS nodes.

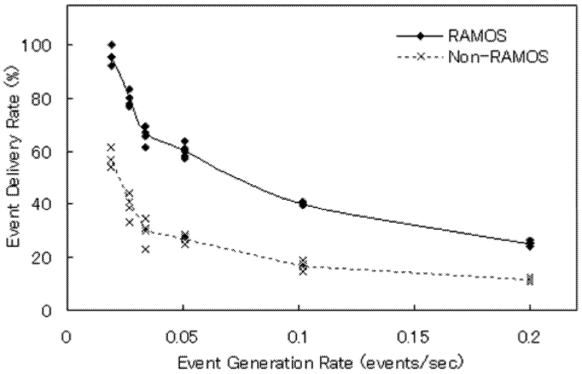


Fig. 5 Case 1: Event delivery rate vs. offered events

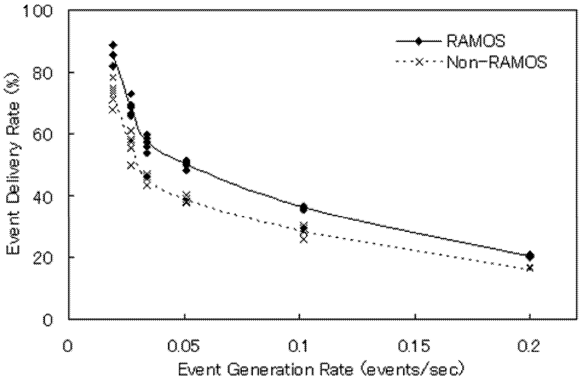


Fig. 6 Case 2: Event delivery rate vs. offered events

In case 2, if M1 becomes out of order, the delivery rate becomes extremely low. To overcome this problem, we are also studying to improve network robustness by the local decision and change the mode. RP mode at previous section is supposed to improve the local robustness by helping other nodes.

Both improving a data delivery rate and network robustness are highly required for more realistic situation such as a disaster area. We defer this as a topic of future work.

4. Related Work

Beaufour et al.[5] studied smart-tag based data dissemination for sensor networks where moving objects, equipped with smart-tags, disseminate data across disconnected static nodes spread across a wide area. Beaufour provides mobile nodes which move randomly and try to distribute data to all nodes, while our work, smart nodes collaborate to increase routing performance and decide the movement by themselves in order to forward data to the destination which may be one or multiple nodes.

LAR[2], GPSR[3], and GEAR[4] are geographic routings that use location information to decrease overhead of route discovery and find routes quickly. GPSR uses greedy forwarding at each hop by routing each packet to the neighbor closest to the destination. When greedy forwarding is impossible, GPSR recovers by routing around the perimeter of the region. GEAR attempts to balance energy consumption and thereby increase network lifetime by selecting next hop from remaining energy and distance from the target region. LAR limits the search for a new route to a smaller request zone.

Fall[7] proposed a delay tolerant networking architecture (DTN) for interoperability between and among diverse networks, especially those composed of resource constrained nodes. It operates as an reliable overlay network and provides key services such as in-network data storage and retransmission, interoperable naming, authenticated forwarding and a coarse-grained class of service. Some preliminary discussions in this work, custody transfer and reliability, congestion and flow control, for example, may be adopted into RAMOS framework.

Hou et al.[8] considered the problem of how to maximize the lifetime for all the nodes in a wireless sensor network. They develop a provably polynomial time algorithm to solve the node lifetime problem, which effectively circumvents the computational complexity problem associated with an existing approach.

Burns[10] proposed MV routing in order to improve a delivery rate in disruption tolerant networks. In their algorithms nodes decide whether forward the data or not by an information of a history of their moving path. They then calculate a probability of successfully delivering a message to a specified area. They also proposed a controller that moves the agent to where network needs are not being met by the movement of peers, and improve the delivery rate. We can consider using the controller to prevent a network from being highly partitioned.

Zhao[9] [11] proposed Message Ferrying (MF) approach which introduces non-randomness in the movement of nodes and exploits such non-randomness to help deliver data in a sparse area. This utilizes moving objects which are assigned to deliver data for destination. However it is required to initialize optimal Ferry route by global decision. In contrast, we are considering nodes behavior by local decision. It is more realistic for such as disaster area.

5. Future Work

In connection-less packet switched networks such as the Internet and MANETs, asymmetric paths are often created; i.e., the returning path between a source and a destination is different from the forwarding path. In RAMOS, this asymmetry becomes more prominent. A mobile robot node that has forwarded data may not stay on the same location when an acknowledgment of the data is returned. Therefore we need to reconsider end-to-end reliability in RAMOS. This also affects the design of TCP over RAMOS. In order to improve delivery rate and network robustness, we are also improving algorithms of changing multiple modes by local decision and doing more experiments.

6. Conclusion

The research community has explored many issues with regard to mobile ad hoc networks. Although networks for mobile robots have several aspects similar to mobile ad hoc networks, there are many challenging issues for the robot networks. We have described issues pertaining to routing assisted by mobile robots and propose the prototype and its results. We also discuss how to improve a performance of mobile robot networks, and observe the requirement of multiple nodes. The routing protocol will be designed differently with mobile ad hoc networks. This routing protocol should be developed in the next few years.

References

1) H. Asama: Distributed autonomous robotic systems, Springler-Verlag (1994)
2) Y. B. Ko and N. H. Vaidya: Location-aided routing (LAR) in mobile ad hoc networks, Proc. of ACM Mobicom 1998 (1998)
3) B. Karp and H. Kung: Greedy perimeter stateless routing for wireless networks, Proc. of ACM Mobicom 2000 (2000)
4) Y. Yu, R. Govindan and D. Estrin: Geographical and energy aware routing: A recursive data dissemination protocol for wireless sensor networks, Technical Report UCLA/CSD-TR-01-0023 (2001)
5) A. Beaufour, M. Leopold and P. Bonnet: Smart-tag based data dissemin ation, Proc. of ACM WSNA 2002 (2002)
6) D. Estrin, R. Govindan, J. S. Heidemann and S. Kumar: Next century challenges: Scalable coordination in sensor networks, Proc. of ACM Mobicom 2003 (2003)
7) K. Fall: A delay-tolerant network architecture for challenged Internet, Proc. of ACM SIGCOMM 2003 (2003)
8) Y. T. Hou, Y. Shi, and J. Pan: A Lifetime-aware flow routing algorithm for energy-constrained wireless sensor networks, Proc. of IEEE MILCOM 2003 (2003)
9) W. Zhao, M. Ammar and E. Zegura: A message ferrying approach for data delivery in sparse mobile ad hoc networks, Proc. of MobiHoc 2004 (2004)
10) B. Burns, O. Brock and B. N. Levine: MV routing and building in disruption tolerant networks, Prov. of IEEE Infocom 2005 (2005)
11) W. Zhao, M. Ammar and E. Zegura: Controlling the mobility of multiple data transport ferries in delay-tolerant network, Proc. of IEEE Infocom 2005 (2005)
12) Mindstorms: http://mindstorms.lego.com/
13) MICA2 Mote: http://www.xbow.com/Products/products details.aspx?sid=72
14) Sensor and data-acquisition boards: http://www.xbow.com/Products/productsdetails.aspx?sid=63.

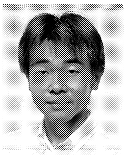
Ryohei Suzuki

He received the BS degree in Information and communication Engineering from Tokyo Denki Univeristy, Japan in 2005. He is currently master's candidate at the Department of Information and Media Engineering at Tokyo Denki University.

Kazunori Makimura

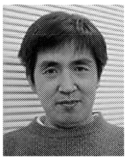
He received the BS degree in Information and communication Engineering from Tokyo Denki Univeristy, Japan in 2004. He is currently master's candidate at the Department of Information and Media Engineering at Tokyo Denki University.

Hiroki Saito



He received Ph.D. degree in Computer Science from Meiji University, Japan in 2001. He is currently an assistant professor in Department of Information Systems and Multimedia Design, Tokyo Denki University, Japan. His research interest includes the sensor networks, the network measurement and the network security.

Yoshito Tobe (Member)



He received Ph.D. in Media and Governance from Keio University in 2000. He is currently a Professorin the Department of Information Systems and Multimedia Design at Tokyo Denki University. His research includes multimedia communications, Internet measurement, wireless sensor networks, and ubiquitous networked sensing. He is a member of ACM, IEEE Communications Society, SICE, and IPSJ.

Reprinted from Trans. of the SICE
Vol. E-S-1 No. 1 52/57 2006