Wireless Video Sensor Networks over Bluetooth for a Team of Urban Search and Rescue Robots

Jaewook Bae
Dept. of Electrical Engineering
University of Minnesota
Minneapolis, MN 55455

Richard M. Voyles
Dept. of Computer Science and Engineering
University of Minnesota
Minneapolis, MN 55455

Abstract - In this paper, we describe a novel routing mechanism to create a low power, high-bandwidth Wireless Video Sensor Network (WVSN) for miniature distributed robots in urban search and rescue (USAR) applications. WVSN features: 1) high-bandwidth, high-quality lossless images, 2) low power, and 3) low latency of data traffic. Traditional proactive network routing schemes exhibit low latency but are impractical for mobile ad hoc networks due to their high control overhead. Reactive network routing schemes are gaining popularity in mobile ad hoc networks, but suffer from high latency when a critical node disappears from the network and are, thus, not desirable for real-time imagery. Our proposed scheme exploits a hybrid ad hoc routing method on top of the low power Bluetooth communication protocol that not only reduces the latency, but also achieves a short routing path. We take advantage of the hybrid combination of proactive and reactive routing schemes to recover a change in the network. We not only simulate a hybrid routing scheme for WVSN, but also implement the proposed scheme on a small team of resource-constrained USAR robots, called TerminatorBot.

Keywords-Ad-hoc network, Routing, urban search and rescue, wireless video sensor network

1. Introduction

Recently, urban search and rescue (USAR) has become a hot issue in robotic research for all venues of ground, sea and air [1][2]. Nearly all current applications of search rely on human interpretation of video images. Under the stress of a real search, the highest quality images are required, so we only consider uncompressed images in this work. (Lossless compression approaches would likely be offset by demand for higher resolutions.) Much of the research in robotic USAR, including those cited, has focused on small size robots to obtain access to confined and dangerous areas that are not directly accessible to a rescuer. Small-size robots provide agility and maneuverability in the tight confines of highly rubbled and uncertain environments as well as providing easy portability and deployability and the potential for redundancy. With the limited resources of these robots, it has been impossible to unite the command data for the robots and high-quality video image data from the robot on a single communication channel. Most existing human/robot interaction devices in this application domain use an analog video feedback channel (wired or wireless) separated from the command and control channel [3].

Interactive command and control for the USAR domain should focus on unencumbered usability for the operator and freedom from tethers for the robot while providing a natural and intuitive interface for users [4]. A robotic tether provides infinite power and the highest quality video to aid the search, but prevents the deployment of a large, distributed robotic team. As the number of tethers increases, the chance for entanglement and obstruction increases nonlinearly. Analog RF transmission has proven to be of questionable quality even with high power transmitters. The large raw data rates of uncompressed video has hindered the development of digital wireless video links that would enable cutting the tether between input interface and USAR robot systems. Traditional mobile ad hoc networks (MANET) either have too low bandwidth for uncompressed video (e.g. Zig-bee) or consume too much power and board area (e.g. Wi-Fi). Accordingly, we adopt the Bluetooth ad-hoc routing protocol to obtain high-bandwidth in a real experiment.

Ad-hoc routing protocols can be divided into two categories: *proactive* or *table-driven* and *reactive* or *source-initiated routing* protocols.

- **Proactive Routing**-This type of protocol periodically maintains all routing information. When a change of the network occurs, alternate routes are known to all nodes and the change notification has to be propagated to maintain up-to-date routing information. (Destination-sequenced distance vector routing(DSDV) [5], cluster head gateway switch(CHGS) Routing [6]).

- **Reactive Routing**-This type of protocol is initiated by only on-demand requests from a source. When a change in the network occurs, link failure notification is propagated to reinitiate the route discovery protocol to find a new route until the message reaches the source.(Ad-hoc on-demand distance vector(AODV) routing [7], dynamic source routing(DSR) [8] [6].

Since all routes are known a priori, a proactive routing scheme is able to instantly respond from a sudden change of the network (lowlatency) as long as an alternate route exists. However, it requires large packet traffic to periodically maintain all routing information over the global network [6]. This may cause network congestion and low effective bandwidth. On the contrary, reactive routing schemes are maintained by source-initiated on-demand requests with relatively lower cost over the ad hoc network. However, it may experience increased latency to recover even a small change of the routing path on a dense network [6] [9]. In order to trade-off their characteristics, [10] and [11] proposed hybrid routing schemes, SHARP and the Zone Routing Protocol (ZRP), respectively. The SHARP proactive routing protocol is a protocol with techniques borrowed from different routing algorithms such as DSDV and the temporally ordered routing algorithm (TORA) [12]. ZRP is based on the routing zone defined by zone radius. It adopts a proactive function locally and a reactive function globally. However, even though these schemes try to separately control the adaptation of the routing layer and minimize packet overhead, it might not be appropriate to WVSN for USAR, which features small and sparse networks. Conventional reactive routing schemes often show better throughput in ad hoc networks than proactive schemes. As Fig. 1 shows, AODV has better throughput during the initial step for the change of the physical topology of a network than DSDV, as long as the updating period of routing information for DSDV is relatively long. So, for some network configurations, reactive routing schemes show better throughput to recover path failure than proactive routing schemes. Hence, in our hybrid scheme, we use a reactive scheme locally to recover a change of the networks with known routing tables obtained by a proactive scheme.

In this paper, we present a novel hybrid routing scheme, which applies a reactive routing scheme to only a local area to recover a path failure and a proactive scheme to a global area. This shows better throughput on a small and sparse WVSN. There are two phases to maintain routing information of the hybrid routing scheme we propose. First phase is that we globally apply a proactive routing method to the whole ad-hoc network infrequently. Second phase is that we locally apply a reactive routing method to the confined area at the point where a path failure of the ad hoc network occurred. In our experiments, we implement a novel protocol using a Bluetooth ad-hoc routing protocol to create a high-bandwidth WVSN for human-in-the-loop control of a USAR robot as shown in Fig. 2.

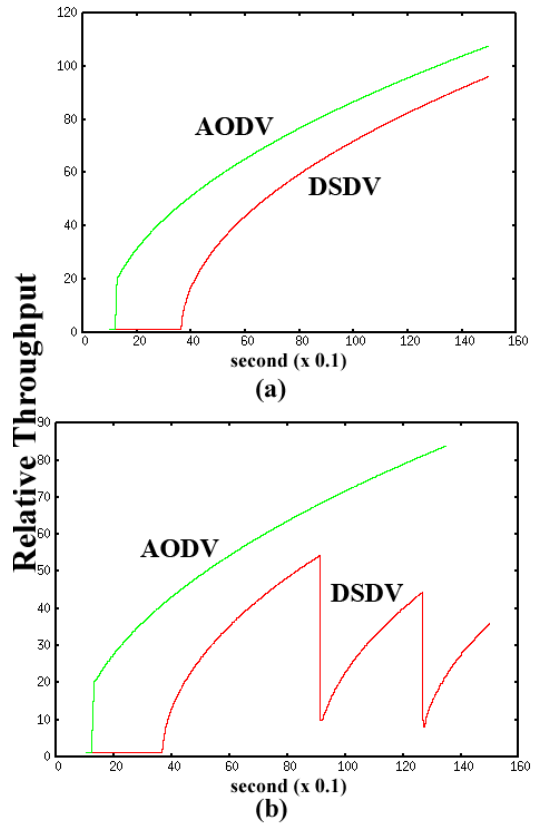

Figure 1. TCP window size with DSDV and AODV when the physical topology of a network changed: (a) 2 nodes(A node approaches to another from out of detection) and (b) 4 nodes(A node disappears from the path)

2. Routing Scheme

In an ad-hoc network for multi-robot search and rescue, the routing scheme that we desire is a highly

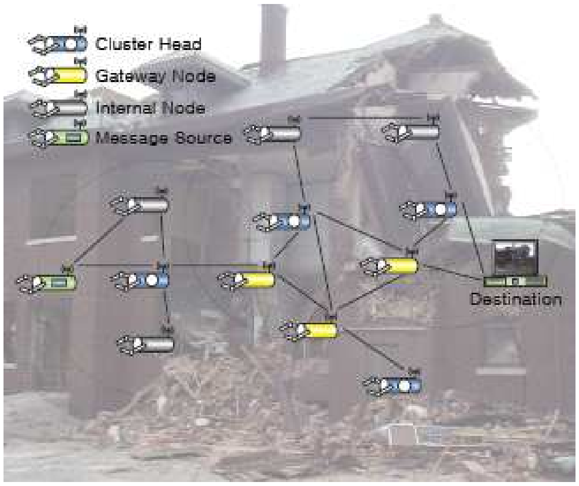

Figure 2. Proactive routing based on cluster head gateway switching

complex and dynamic model specific to the intended purpose. The USAR robot features compact size, limited power and other resources, and unpredictable movement. Even a small movement might change the whole network topology. Therefore, the routing scheme should be able to cope with unexpected factors of the surroundings. The network environment in USAR is consistent with MANET. In MANET, we exploit the hybrid characteristics of proactive and reactive routing for WVSN on USAR. The routing protocol for WVSN not only has to provide high-bandwidth to transfer large lossless images over the network from source to destination, but it also must respond quickly to recover from failure or change of paths with an appropriate network recovery algorithm.

2.1. Wireless Video Sensor Network

A WVSN consists of a source node, multiple intervening carrier nodes, and a destination node. (Source and destination nodes might change as the mission evolves, but this can be considered quasi-static.) The source is a mobile robot including a visual sensor to grab a sequence of image frames. Image data captured from the source is delivered by carriers between the source and destination. The carriers should be able to quickly transfer the image data to another carrier or the destination without modification of the data. Hence, the number of the carriers involved contributes to the latency of the network. The destination (often an operator console), which has high computing power, analyzes the image data received or displays it for human analysis. WVSN on USAR can be characterized as:

- High mobility and unpredictable movement.
- Sparse network.
- High bandwidth.
- Low node resources (energy, computing, and memory).

2.2. Bluetooth Communication on USAR

[13] and [14] introduced bluetooth communication to coordinate distributed robots in a point-to-point manner. For distributed robots, many robotic researchers tried to use wireless communication technology but it was vulnerable to noise at long distances and ad-hoc networking has been difficult in highly mobile scenarios. Recently, Bluetooth and Zig-bee technology represent wireless network communication in the distributed robotics field. The range of Bluetooth is shorter than Zig-bee in the ad-hoc network, but the communication speed of Bluetooth is four times faster than Zig-bee. The high channel bandwidth of Bluetooth allows us to efficiently transmit uncompressed image data without traffic congestion.

Bluetooth features low cost, low power, and use of the unlicensed 2.4 GHz band. Bluetooth communication can be typically created in a spontaneous manner. Hence, ad-hoc networks for Bluetooth don't require a formal infrastructure [15]. In an ad-hoc network of USAR robots, due to the high mobility of each node, it is difficult to predict the topology of the network in advance. The ad hoc network may randomly change the topology of links regardless of formal network structure. With this reason, many research literatures have focused on the efficient allocation of the roles of cluster head and nodes and routing protocol schemes in an ad hoc Bluetooth network [16] [17]. A local topology, called piconet, links a master and slaves and obviously conform with an asteroidal topology [16]. In Fig. 3, the master assumes the role of managing the routing information of the slaves in the piconet. A global ad-hoc network area, scatternet is a global ad-hoc networking method to link several piconets. In order to obtain the goal of this scatternet topology, each master should be aware of its slaves, gateways and up-to-date routing information that other masters are maintaining in Fig. 4.

2.3. Hybrid Proactive and Reactive Routing Method

Our goal is to combine the benefits of proactive and reactive routing to achieve high bandwidth and low latency over a low power network. In order to achieve

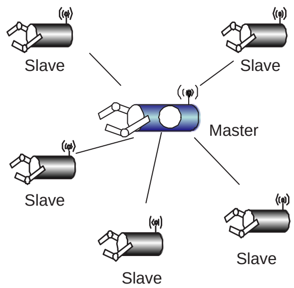

Figure 3. Piconet: Links of a master and slaves

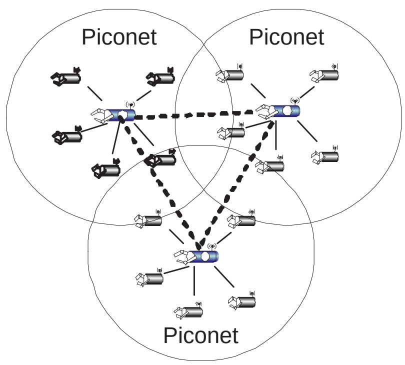

Figure 4. Scatternet: Links of piconets

the goal, there are two considerations: quick failure recovery of the routing path and low cost of maintaining routing information. In the proactive routing method, the routing table is frequently updated by exchanging change-and-update messages between masters. In this mechanism, we can effectively cope with a very sudden change in network topology, as long as a backup route exists. However, the update and acknowledge messages of the protocol might abuse the network resource. Conversely, the reactive routing method can take a load off the network resource to manage the routing table. However, it might be vulnerable to find the shortest path for a sudden change of network topology, as long as it doesn't make a failure on the current routing path. In our approach, we adopt the cluster head gateway approach in which only masters are represented in the routing table, reducing routing traffic. Furthermore, we only infrequently invoke the proactive routing scheme to update the routing table of master nodes. (Slaves are indexed to a particular master that appears in the table.) The updating period of the hybrid routing method is much less than proactive routing scheme as it is only invoked when a failure occurs. When a path failure occurs, we only locally apply the reactive routing scheme to that area. It allows us to cope with the failure much faster than the proactive scheme. The number of involved nodes to update the routing information is much smaller than the DSDV or AODV methods. The overall of the schemes is presented in Fig. 5. Fig. 5 (c) shows the sequence flowchart for our proposed method.

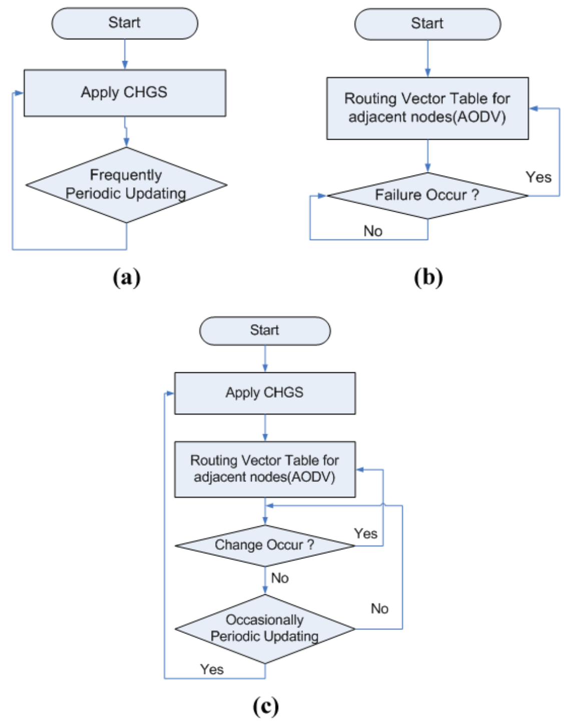

Figure 5. Sequence flow chart of updating routing information: (a)Proactive routing scheme, (b)Reactive routing scheme, and (c)Hybrid proactive and reactive routing method

3. Simulation and Experiment

We tackle the analysis of our hybrid algorithm with both simulation and experiments with a USAR robot. The simulation software allows us to test larger video sensor networks we can't currently implement with our small team of physical robots.

3.1. Simulation Software

We built our own simmulator for our network algorithm, the user interface of which is shown in Fig. 6 We deployed 10 robots in software in Fig. 7 (a). At the initial step, all robots are not assigned as a master or slave except a source and a destination robot. For convenience, we assign the source and the destination robot as masters. Then, the software can easily assign all robots as a master or slave in global network in Fig. 7 (b) in [18]. Once assigned, the source is sending raw

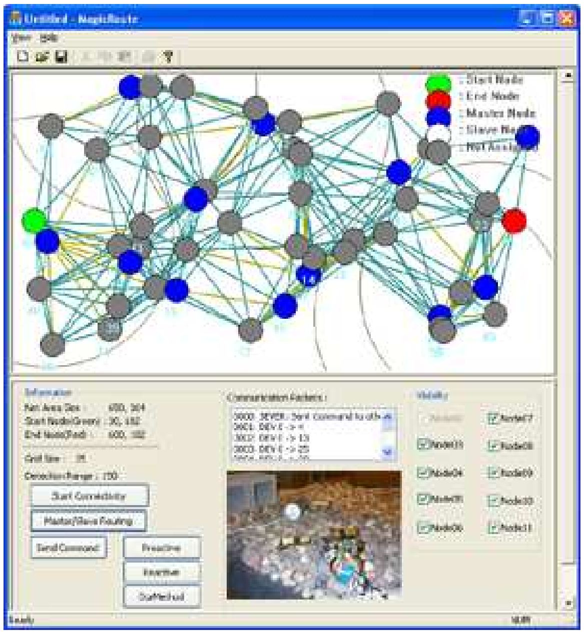

Figure 6. WVSN simulation software: Routing Simulation for 50nodes

image data through the route built by proactive routing method in Fig. 7 (b). During the operation, we take a master away from the network to make a worst case when a master containing the local routing table disappeared Fig. 7 (c). Some existing literatures dealing with proactive routing method have to wait until a global routing table is updated. However, in our novel algorithm, we can determine an alternative path by using reactive routing method in Fig. 7 (d). This method can cope with the frequent change of the network with low cost of routing protocol in distributed USAR robots. In Fig. 8, we can see that our method shows a prominent result in recovery time for 50, 100, 150, and 200 nodes. Thus, we can preestimate the result of recovery time regardless of the number of nodes in network. The result of the simulation also shows better than proactive routing method, CHGS, and reactive routing method, AODV.

3.2. Implementation and Experiment

The fieldable version of the TerminatorBot (Fig. 9) employs an 8-bit Atmel microcontroller for communications and control. Our custom embedded controllers employ the Infineon Bluetooth module, ROK 104 001/2 R1B, for communications. To test the routing scheme, we employed two of these microcontroller nodes and three Bluetooth-enabled laptops to create a small, 5-node network to transfer a static image file. the source

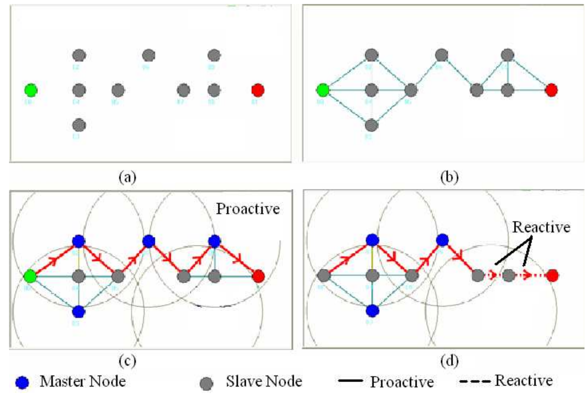

Figure 7. The result of simulator: (a) Initial deployment of robots (b) scanning discoverable devices through Bluetooth (c) Allocation of master/slave by using proactive routing method (d) Recovery of a change in local area by using reactive routing method

and destination nodes were hard-coded for this case.

As a testing framework, we measured the packet data required for updating the routing information and the latency when the critical master node (see Fig. 10) was removed during message transmission. The loss of a master on the routing path is the worst case failure mode. The loss of a slave not on the path is almost irrelevant. (Only a minor potential for latency impact.) Likewise, the loss of a master not on the path carries only the potential penalty of reorganizing masters. The loss of a gateway slave node is only a minor impact as the master knows all its slave nodes and can pick a replacement. Thus, in this test, we prove the efficiency of the hybrid scheme in such a case which may happen frequently in sparse ad-hoc networks.

In order to perform the test, we were limted to 57,600 bps communication protocol between the microcontroller and the Bluetooth communication module. Although this is well below the 1Mbps needed for uncompressed images, it demonstrates proof of concept. We also used a static data file to transfer over the network instead of real image data. The designated data could be considered as a real image and results in an accurate characterization of the network. We applied CHGS, AODV and our own hybrid scheme to the test. The CHGS updated global routing information between the master nodes every 60 seconds.

In Fig. 10, the source node kept sending the data to the destination node through the critical master node until the data arrived at the destination. The destination checked out the arrival time and latency of the data. Slave nodes were used as gateways between mas-

Routing method	No Failure	Worst Case
CHGS	Update Packet(bytes): 45 Avg. Latency(msec) : -	45 34000
AODV	Update Packet(bytes): 0 Avg. Latency(msec) : -	35 21.6
Hybrid	Update Packet(bytes): 45/2 Avg. Latency(msec) : -	17 4

Table 1. Experimental data for recovering the worst case

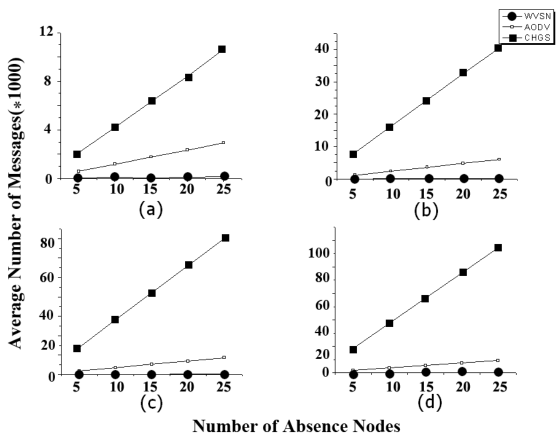

Figure 8. The simulation comparison of required routing update packet for proactive routing, reactive routing and our hybrid method, respectively: (a) for 50 nodes (b) for 100 nodes (c) for 150 nodes (d) for 200 nodes.

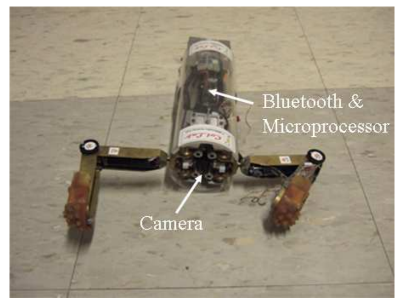

Figure 9. A TerminatorBot

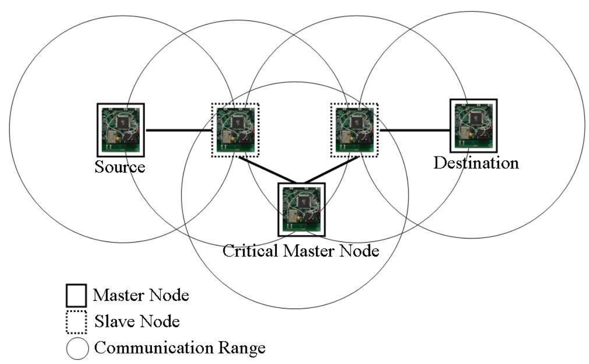

Figure 10. The worst configuration of the WVSN

ter nodes. The critical master node on the path was then removed and the time and latency of the packet data was computed. The result is shown in Table 1. As the table indicates, the hybrid method showed the best latency performance in the worst case scenario. In comparing the ”no failure” operation from Table 1, AODV performed best. Of course, the “no failure” condition is unrealistic for any type of mobile network, and is particularly unrealistic for sparse, mobile, and highly unpredictable networks of urban search and rescue.

4. Conclusion

In this article, we described an efficient hybrid routing scheme to transfer raw image data over a Bluetooth ad-hoc sensor network. This scheme has introduced a fast self recovery algorithm to reduce latency and packet control overhead by confining the re-discovery protocol to the area local to the network failure. We have also shown a quantitative comparison of proactive, reactive and hybrid routing methods in representative sparse ad-hoc network topologies. We demonstrated, both in small physical networks and larger simulations of networks, the benefit of our hybrid routing method to sparse networks of highly mobile nodes in terms of reduced latency assuming a common radio transport layer. Although we limited the throughput for our physical experiments, the use of Bluetooth as our transport layer achieves the low resource consumption (power and physical size) while holding the promise of full-rate video transmission.

References

[1] K. Osuka and H. Kitajima, "Development of mobile inspection robot for rescue activities: Moira," in *Proceedings of the IEEE Conf. on Intelligent Robots and Systems*, 2003, pp. 3373–3377.

[2] W. Green and P. Oh, "An aerial robot prototype for situational awareness in closed quarters," in *Proceedings of the IEEE Conf. on Intelligent Robots and Systems*, 2003, pp. 61–66.

[3] P. Rypski, S. Stoeter, M.Gini, D. F. Hougen, and N. P. Pananikolopoulos, "Performance of a distributed robotic system using shared communications channels," *IEEE Transactions on Robotics And Automation*, vol. 18, no. 5, pp. 713–727, Oct. 2002.

[4] M. Voshell, D. D. Woods, and F. Phillips, "Overcoming the keyhole in human-robot coordination: simulation and evaluation," in *Proceedings of the Human Factors and Ergonomics Society*, 2005, pp. 26–30.

[5] C. E. Perkins and P. Bhagwat, "Highly dynamic destination-sequenced distance-vector routing(dsdv) for mobile computers," in *Computer Communications Review*, Oct. 1994, pp. 234–244.

[6] E. M. Royer and C. K. Toh, "A review of current routing protocols for ad hoc mobile wireless networks," pp. 46–55, Apr. 1999.

[7] C. E. Perkins and E. M. Royer, "Ad-hoc on-demand distance vector routing," in *Second IEEE Workshop on Mobile Computer Systems and Applications*, 1999, pp. 99–109.

[8] D. Johnson and D. Maltz, "Dynamic source routing in ad hoc wireless networks," in *Mobile Computing*, 1996, pp. 153–181.

[9] M. Mauve, J. Widmer, and H. Hartenstein, "A survey on position-based routing in mobile ad hoc networks," pp. 30–39, Nov. 2001.

[10] V. Ramasubramanian, Z. J. Haas, and E. G. Sirer, "Sharp: A hybrid adaptive routing protocol for mobile ad hoc networks," in *The Fourth ACM International Symposium on Mobile Ad Hoc Networking and Computing*, 2003, pp. 303–314.

[11] Z. J. Haas, "A new routing protocol for the reconfigurable wireless networks," in *IEEE 6th ICUPC*, vol. 2, no. 12, Oct. 1996, pp. 747–752.

[12] V. D. Park and M. S. Corson, "A highly adaptive distributed routing algorithm for mobile and wireless networks," in *Proceedings of IEEE INFOCOM*, Apr. 1997.

[13] S. H. Whang and K. B. Sim, "Bluetooth network for distributed autonomous robotics system," in *International Conference on Control, Automation and Systems*, Kyeonggi-Do, Korea, June 2005.

[14] J. McClain, B. Wimpey, D. Barnhard, and W. Potter, "Distributed robotic target acquisition using bluetooth communication," in *Proceedings of the 42nd Annual ACM Southeast Conference*, Huntsville, Alabama, Apr. 2004, pp. 291–296.

[15] "Bluetooth specification version 1.2," in *http://www.bluetooth.org*, vol. 1.

[16] Z. Jian, Z. Fei, and W. Bin, "Cluster based routing in bluetooth ad-hoc network," in *Proceedings of Wireless Communications, Networking and Mobile Computing*, vol. 2, no. 12, Sept. 2005, pp. 747–752.

[17] A. Greede and D. O'Mahony, "A service driven routing protocol for bluetooth," in *In proceedings of 5th European Personal, Mobile Communications Conference*, Glasgow, Scotland, Apr. 2003, pp. 307–311.

[18] C. C. Chiang, "Routing in clustered multihop, mobile wireless networks with fading channel," in *Proceedings of IEEE SICON*, Apr. 1997, pp. 197–211.

[19] S. Lee and M. Gerla, "Aodv-br: Backup routing in ad hoc networks," in *Proceedings of IEEE WCNC 2000*, Chicago, IL, USA, 2000, pp. 26–30.

[20] P. Papadimitratos, Z. J. Haas, and E. G. Sirer, "Path set selection in mobile ad hoc networks," in *The Third ACM International Symposium on Mobile Ad Hoc Networking and Computing*, 2002, pp. 1–22.

[21] S. J. Lee and M. Gerla, "Aodv-br: Backup routing in ad hoc networks," in *IEEE Wireless Communications and Networking Conference*, 2000, pp. 1311–1316.

[22] R. M. Voyles, A. C. Larson, M. Laoint, and J. Bae, "Core-bored search-and-rescue applications for an agile limbed robot," in *Proceedings of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 1, 2004, pp. 58–66.

[23] K. Newman, "The open interface: Beyond keyboards and mice," pp. 58–66, May 2002.

[24] R. Voyles and A. Larson, "Terminatorbot: A novel robot with dual-use mechanism for locomotion and manipulation," *IEEE/ASME Transactions on Mechatronics*, vol. 10, no. 1, pp. 17–25, 2005.

[25] R. M. Voyles, "Terminatorbot: A robot with dual-use arms for manipulation and locomotion," in *Proceedings of the 2000 IEEE International Conference on Robotics and Automation*, San Francisco, CA, USA, Apr. 2000, pp. 61–66.

[26] D. H. Barnhard, B. J. Wimpey, and W. D. Potter, "Odin and hodur: Using bluetooth communication for coordinated robotic search," in *Proceeding of the International Conference on Artificial Intelligence*, Las Vegas, Nevada, USA, 2004.

[27] J. Lee, K. Son, M. C. Lee, S. Han, and M. Lee, "Localization of a mobile robot using the image of a moving object," *IEEE Transactions on Industrial Electronics*, vol. 50, no. 3, pp. 612–619, June 2003.