The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

An Adaptive Mobile Robots Tethering Algorithm in Constrained Environments

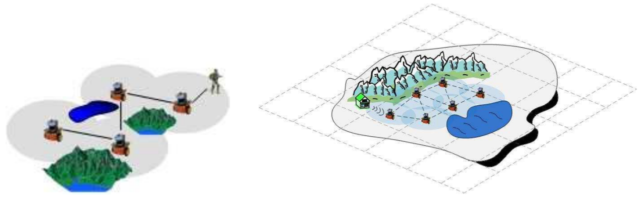
Xi Chen and Jindong Tan

Abstract— **This paper presents an adaptive and decentralized robotic cooperation algorithm for controlling the mobile sensors to form a chained network and maintaining the communication links. A single-layer and double-layer chain tethering algorithms are developed for exploring the open and constrained environments by mobile robots. A comprehensive metric for finding the optimal communication range is introduced. With the measurements, mobile robots could be organized into an optimal chained form for tethering. The tethering algorithm could detect the failed nodes and reconfigure the system. It offers an adaptive solution to broken communication links.**

I. INTRODUCTIOIN

Recently, the advancement of technology has accelerated the application of wireless sensor networks. Moreover, mobile sensor networks are attracting more attentions due to their advantage of mobility and adaptability in complicated environments. Their wide applications cover battlefield surveillance, rescue operations [1], exploration of special environments [2], [3], and even robotic soccer games [4]. Additionally, mobile sensor network could do tethering in constrained environments. When mobile robots are deployed in an unknown environment without preconfigured infrastructure, they organize into a network by communication. Compared with static wireless sensor networks, mobile robots could adjust their movements according to the variance of environments, in order to maintain the communication links between sensor nodes. This mobility could increase the flexibility of the network formation. The goal of mobile sensor network tethering is not only organizing and maintaining the communication links, but also could maximize the end-to-end distance in constrained environments. Especially for some narrow regions or special terrain, this tethering performs better than traditional mobile sensor network deployment.

There are many different types of network topology and among those the mesh network is more reliable. However in constrained environments, it appears some drawbacks such as high redundancy and costly expense. It is better that mobile sensor network could maximize the end-to-end communication distance with minimal numbers of robots. Thus chained form network suitably works for this situation. Fig. 1(a) shows a scenario that a single-layer chained network is set up in a natural setting which includes mountains and lakes. The mobile robots try to maximize their end-to-end communication distance according to the constraints around. End devices in the network could communicate with others even they are out of sight. However, the single-layer chain tethering has a fatal problem. By means of leader-follower strategy to control the movement of robots, if one or some robots in the single-layer chain are lost due to the factor of node broken or other factors, the network would be totally separated. A solution to this problem is double-layer chain tethering, as Fig. 1(b) shows. It offers a more robust solution to network tethering problem. If one of the robots is failed, the others can still be in touch with other robots and end devices in the network. Since providing connectivity of the networks through the relay is more significant in an unknown environment, we mainly work on how to control the mobile robots to organize an optimal network in a flexible formation.



(a) Single-layer chain tethering

(b) Double-layer chain tethering

Fig. 1. Chained structure mobile sensor network

There are three major problems need to be addressed for developing the tethering algorithm. First is the challenge from the estimation of communication link quality. Second is the network architecture. Third is the control strategy for network tethering.

Communication link estimation is critical in maintaining the mobile sensor network. It is always expected that the network could be optimally organized with maximum communication range of each mobile robot. However, the maximum communication range is highly relying on the exact estimation on communication link quality. Many approaches for estimating the communication link quality have been considered, *i.e.* Signal-to-noise ratio (SNR), throughput, Packet Loss rate (PLR), Link Quality Indicator (LQI) and Received Signal Strength Indicator (RSSI), etc. The choice should be compared with all their advantages and disadvantages, and considered the convenience and efficiency for installing and employment existing devices.

The critical parameters achieved from communication link estimation could help building the model of chained form

---

This work is supported in part by the National Science Foundation under Grant ECS #0528967 and CSR #0720781, ARL under contract W911NF-06-2-0029 and CERDEC W15P7T-06-P228, and TARDEC.

Xi Chen and Jindong Tan are with the Department of Electrical Computer Engineering, Michigan Technological University, Houghton, MI 49931, USA {`xchen3,jitan`}`@mtu.edu`

network. Each transmitting node has a larger interference range and a smaller communication range. When developing the communication program for chained form network tethering, the node sequence of transmitting needs to be analyzed carefully in case of the interference from other transmitting node. Different situations of communication collision in MAC layer are considered in the round in this paper.

The mobile robots aim to optimally maintain the communication links and cover the communication gaps in the network. The leader-follower strategy could control the autonomous robots to explore a certain environment in a chained formation. When leader robot is requested to explore the unknown environment, its follower would decide the next position according to the movement of leader robot and current environment. Every node follows its leader(s) in a decentralized way and the chained form network could move in a curving trajectory with an ideal layout.

II. RELATED WORK

There has been considerable works in studying the estimation of communication link quality and multi-robot cooperative control. And some graphic theoretic concepts and chained form structure in robot control algorithms are drawing many attentions in recent years.

Since in some special RF environment, position based chained solutions are not possible respond to changes. Thus some approaches to maintain communication chain based on link quality estimations were developed. Based on Shannon-Hartley theory, the capacity of communication links are proportional to SNR. Dixon and Frew employed SNR of the individual communication channels to form an optimal communication chain of robotic relays [5]. Extremum Seeking (ES) control algorithm was presented to drive the team of robots to optimal locations with local measures of SNR [6]. In their work, SNR was used as input into the ES control system to improve and maintain communication performance. Apart from using SNR to evaluate link quality, researchers adopted Received Signal Strength to assess the quality of connectivity in multi-robot system. Though RSSI is varying and bad for localization, this variation can be used to leverage network repair precisely. Luthy et al. used RSSI measurements for simple navigation and placement by mobile nodes [7]. Besides, Packet Loss rate also can serve as a metric to reflect the performance of communication links.

Graph theoretic concepts for mobile robots deployment have been taken much attention recently. In [8], a scalable graph model for decentralized control of mobile robots was discussed. Some graph theoretic concepts were also used in [9]. In [10], an optimal deployment layout of nodes was found. Equilateral triangulation was proven to be the optimal layout to provide the maximum no-gap coverage. Das et al. defined a directed graph which was used to control the formation of a group of mobile robots [11]. After electing the leader of the group, robots used sensory information to establish their neighbors and construct a spanning tree rooted at the leader. A default control graph was established by the spanning tree, and it was adapted and refined depending on the shape of the formation and environmental conditions.

Chained form formation can be used to maximize the end-to-end throughput using a cooperative team of mobile robotic relays. In [5], an optimal communication chain with one-layer structure was defined to maximize the end-to-end throughput while allowing the end nodes of the chain to moving independently. The performance of communication chain was directly influenced by the motion and location of the mobile relay within the network. In [11], a set of algorithms were presented that allowed a group of mobile robots to organize them into a specified formation. In this work, a double-layer chained structure was mentioned to verify the stability of the control graph. Virtual potential theory has been developed for avoiding obstacles and collision of robots when controlling a robot. Also virtual forces affect the movement of each robot. Such collection can be found in [12], [8], [10].

III. COMMUNICATION AND NETWORKING OF CHAINED FORM TETHERING

In this section, we briefly introduce the estimation of communication link quality. According to the critical parameters we obtain from the estimation, a link quality model could be defined. Based on the model, network architecture is defined and MAC layer collisions in different situations are considered, in order to avoid communication interference during transmitting.

A. Communication Link Quality Estimation

The analysis of three metrics: RSSI, throughput and PLR, and their related effects on estimating the communication link quality are introduced in this part.

1) RSSI: In wireless communication area, RSSI is a measurement of the power presents in a received radio signal. It uses average power to calculate its value, therefore RSSI can be adopted as a metric to evaluate the link quality. RSSI measurement from mobile sensor networks could be directly acquired using existing network devices in IEEE 802.11 protocol. The RSSI measurement is monotonic decreasing with increase of distance between two transmitters. However in mobile sensor networks, the RSSI measurement is prone to be affected by surrounding environments and some factors from robot itself. So some specialties like mobility and position uncertainty should be considered before putting sensor networks into effect.

2) Throughput: Throughput as a conventional metric in communication network reflects the performance of communication capacity [13]. If a robot moves into a ”gray zone” [14] or extremely noisy area, although the RSSI measurements could decay by a small value, the link is broken possibly. There exists a point from where the communication link start decaying. However, RSSI can’t point out this critical point. Throughput is a good monitor to estimate this saturation point of a link. So it is prone to be accepted as a complement for the evaluation of communication link quality.

3) PLR: PLR is a real-time detector to estimate the threshold of network health status. It can directly illustrate communication link quality in wireless network. However in real experiments, the cutoff area of communication link is so narrow that the robots could not respond to actions in time. Thus, PLR is not suitable to be a feedback for controlling the robotic team, but fit for detecting the cutoff area in a communication link.

4) Summary: RSSI is suitable for evaluating the communication link quality. Meanwhile, throughput could be a generator for providing the threshold for stable transmission. Similarly, PLR shows where the communication cutoff point exists. If the distance is beyond cutoff value, the connection between neighbors could be easily broken. The relation between the critical points is shown in Fig. 2. As long as the mobile robot stays in a circle with the radius less than saturation value (robot A and B are within the inner circle), then the communication links could retain connectivity; if the robot moves out of the inner circle (robot A and C are within the outer circle), it still has the ability to exchange data with neighbors but the throughput would sharply fading; if two neighbors are far beyond their saturation point, even out of cutoff value (robot D is beyond outer circle), then they will totally lose connection. Such critical points should be calculated precisely in different environments due to their variance in diverse situations.

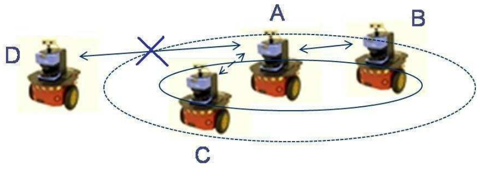


Fig. 2. The impact of distance on communication link quality

Motivated by the connectivity in multi-robot team [9], we define the quality of communication link between one-hop neighbor R_i and R_j as a continuous value, which is denoted by improved RSSI measurements. The link quality is set to be:

$$\psi_{ij} \triangleq \begin{cases} \Delta_{ij}, & \|p_{ij}\| < \rho \\ 0, & \|p_{ij}\| > R \\ exp[\frac{-5(\|p_{ij}\|-\rho)}{R-\rho}], & \text{otherwise} \end{cases} \tag{1}$$

where p_{ij} is the improved RSSI value between robot R_i and R_j, ρ means a saturation RSSI measurement where the communication link quality between neighbor robots does not change even if they get closer to each other and R means the cutoff RSSI measurement which could guarantee the link connection. Nevertheless different from the idea in [9], we define Δ as a variant which describes the degree of the connectivity of neighbors.

B. Networking

Mobile sensor networks are battery operated, so a low power consuming MAC protocol would enable a successful operation of the networks. There are many works talking about adopting MAC protocol to avoid communication collisions and overhearing, such as S-MAC [15], B-MAC [16] and etc. S-MAC protocol aimed to reduce energy consumption and fault rates with periodic sleep. However, it existed the trade-off between fairness/latency and energy. B-MAC protocol combined several advantages from previous work and resolved the trade-off problems. Currently, B-MAC protocol is often considered as the default WSN MAC protocol. Thus, our network protocol is inspired by such existing protocols. In order to avoid hidden terminal problem and exposed terminal problem, our double-layer chained network adopts time sharing method to arrange the sequence of transmitting. In each time slot, only one node can transmit data to neighbors, except two transmitting nodes are beyond their interference range. An appropriate MAC protocol ensures the communication working in the low fault rate.

With the help of communication link quality estimator, our decentralized control algorithm could organize the mobile sensors to form an optimal layout. Fig. 3 shows the final layout of a double-layer chain tethering with mobile nodes.

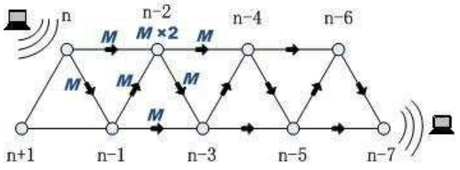
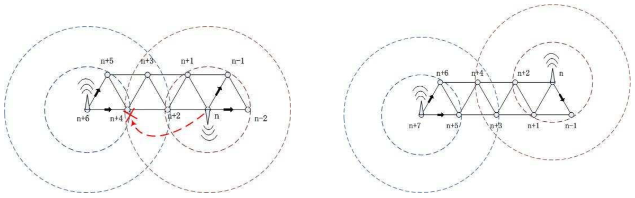


Fig. 3. Redundancy in double-layer chain communication

The message is broadcasted in this cascaded triangle, each neighbor of the transmitter could receive the message. In our design, we assume that the message is always transmitted from node(n) to node($n+m$) or node($n-m$), in which direction depends on the location of end devices. As Fig. 3 shows, when node(n) detects an event happening, it originates a message M to its neighbors, node($n-1$) and ($n-2$). Aiming to transmit M to the end device near node($n-7$), the process continues round by round. Except for the initial transmission by node(n), all nodes receive two copies of M from two different followers. So next, node($n-1$) forwards M to its leaders, node($n-2$) and ($n-3$). Because of the structure of double-layer chain, node($n-2$) receives M twice, which provides dual data redundancy. It is known that data redundancy could be a main factor results in low efficiency in sensor network. However, it is necessary for fault tolerance in double-layer chain network.

In this double-layer chained network, when one node is transmitting messages, within whose interference rage two neighbor nodes can only receive the messages. Otherwise, some collisions would occur. We considered different situations which would cause a collision. As we stated before, each sensor node has a larger interference range and a smaller communication range. In Fig. 4(a), node(n) and ($n+6$) are transmitting messages at the same time. Although node(n) is not transmitting the message to node($n+4$), however, node(n+4) could hear the message from node(n+6) and interfered by node(n). Then the collision would occur at node($n + 4$). From this example, all the situations of collision could be summarized: node(n) and node($n \pm m$) are transmitting at the same time, when $m <= 6$, collision occurs in MAC layer; when $m > 6$, as Fig. 4(b) shows, no collision occurs in MAC layer. Thus, the number m in a network should be larger than six. In order to avoid communication collisions in MAC layer, such situations should be considered completely before developing the network protocol.



(a) Situation of node(n) and node($n \pm 6$)

(b) Situation of node(n) and node($n \pm 7$)

Fig. 4. Situations of MAC layer collision and no collision

IV. GRAPHIC MODEL BASED CONTROL ALGORITHM

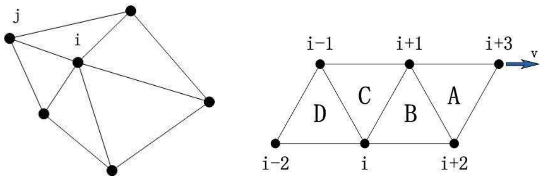
In this section, based on graphic theory and our previous work [8], we defined a decentralized control algorithm for double-layer chain tethering. The graphic model based control algorithm could drive the double-layer chained network to translate, rotate, expand and contract itself in open environment, which also provides a more adaptive control strategy for complicated constrained environment.

A. In Open Environment

An open environment refers to places where there are no intensive interference and obstacles. In this kind of environment, the objective of tethering is to maximize the end-to-end distance without considering the obstacles. The kinematic model for mobile robot R_i is given by:

$$\dot{\mathbf{x}}_\mathbf{i} = \mathbf{f}(\mathbf{x}_\mathbf{i})\mathbf{u}_\mathbf{i} \tag{2}$$

where $\mathbf{x}_\mathbf{i} = (x_i, y_i, \theta_i)$, and $\mathbf{u}_\mathbf{i} = (v_i, \omega_i) \in \mathbb{R}^2$ is inputs. v_i and ω_i are the linear and angular velocities of robot R_i.



(a) Initial deployment

(b) Final layout

Fig. 5. Initial deployment and final layout of double-layer chained network

For our double-layer chained network, each network has a finite set of robots, $R_1, R_2, ..., R_n$. Before tethering, some mobile robots are randomly deployed in a region. As Fig. 5(a) shows, robot R_i has five connections with its neighbors, and all rest robots have three connections. Compared with the final layout of double-layer chained network, it is seen that all the robots have four connections except first two and last two robots. From Fig. 5(b) we can see, robot R_i has four connections with neighbors: l_{ij}, for $j = \{i-2, i-1, i+1, i+2\}$, which are included in three cascaded triangles($\triangle B, \triangle C, \triangle D$). Because each triangle in the final layout is equilateral triangle, it offers a stable structure for double-layer chained formation. Meanwhile, for any neighbor robots R_i and R_j:

$$\forall i, j \quad \{|i - j| = 1 | l_{ij} = d\}$$

where d is the minimal communication range of mobile nodes.

When one node is selected as the leader, it starts moving. Then it chooses the closest neighbor as its follower. As they move on, the follower chooses its closest neighbor. The new follower follows its two leaders and forms the triangle with our control algorithm. The process continues until the network is formed. The leader robot of double-layer chained network is quite important, which leads the moving of the chain. In Fig. 5(b), leader robot R_{i+3} determines the direction of $\triangle A$, and robot R_{i+2} leads the direction of $\triangle B$, *etc*. A scalar variable s is used for parameterizing the motion of network, in order to makes the control strategy easier.

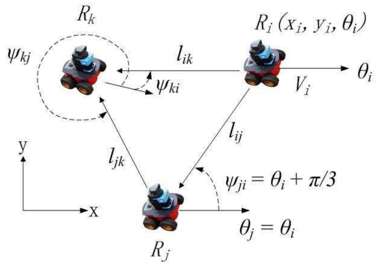


Fig. 6. Triangle formation of the first 3 mobile robots

Each robot in this network should follow its two neighbors, so it has at most two inputs. As the first equilateral triangle shown in Fig. 6, if robot R_j has only one input, we can confirm that R_j is following the first leader of the network R_i. Additionally, if we know the position and orientation of the leader of the network R_i, *i.e.* $\mathbf{x}_\mathbf{i} = (x_i, y_i, \theta_i)$, then we can get the desired coordinates of the second robot R_j:

$$\begin{aligned} l_{ij} &= \sqrt{(x_i - y_i)^2 + (y_i - y_j)^2} \\ \psi_{ji} &= \pi - \arctan 2(y_i - y_j, x_j - x_i) - \theta_j \\ \theta_j &= \theta_i \end{aligned} \tag{3}$$

where ψ_{ji} is the angle from the heading direction of robot R_j to robot R_i. In our network, we force that:

$$l_{ij} = d, \quad \psi_{ji} = \theta_i + \frac{\pi}{3}$$

Then we could get the position and orientation of robot R_j, $\mathbf{x}_\mathbf{j} = (x_j, y_j, \theta_j)$. Robot R_k follows its two leaders R_i and R_j. And from Eqn. 3, we let l_{ik} and l_{jk} both equal to d. Thus robot R_k knows its position for next round and then controls itself to move to the position and maintain the formation with its two leaders. For the rest of robots, they use the same control strategy as robot R_k and drive the formation moving forward.

In this triangle, robot R_i has two degree of freedom (DOF); robot R_j has one DOF; robot R_k has zero DOF. Hence we define that in each triangle in the network, the robot who has two DOF is the leader of this triangle; who has zero DOF is the last follower of this triangle. As we stated before, in Fig. 6, the position of robot R_i is given by $\mathbf{x_i} \in \mathbb{R}^3$. Let $\mathbf{x_{ki}} = \mathbf{x_k} - \mathbf{x_i} \in \mathbb{R}^3$ and $\mathbf{x_{kj}} = \mathbf{x_k} - \mathbf{x_j} \in \mathbb{R}^3$. We define an artificial potential $V(\mathbf{x_{ij}})$ between every pair of robots R_i and R_j, which depends on the distance between them. Inspired from [12], for a group of M robots the control law u_k is defined as below:

$$\begin{aligned} u_k &= -\sum_{i\neq k}^{M} \nabla_{\mathbf{x_k}} V(\mathbf{x_{ki}}) - \sum_{j\neq k}^{M} \nabla_{\mathbf{x_k}} V(\mathbf{x_{kj}}) - K\dot{\mathbf{x_k}} \\ &= -\sum_{i\neq k}^{M} \frac{f(\mathbf{x_{ki}})}{\|\mathbf{x_{ki}}\|}\mathbf{x_{ki}} - \sum_{j\neq k}^{M} \frac{f(\mathbf{x_{kj}})}{\|\mathbf{x_{kj}}\|}\mathbf{x_{kj}} - K\dot{\mathbf{x_k}} \end{aligned}$$

where K is a positive-define matrix. It defines as minus the sum gradient of these potentials plus a linear damping term. Potential V yields a force: when $\|\mathbf{x_{ij}}\| < d$, force is repelling; $\|\mathbf{x_{ij}}\| > d$, force is attracting; $\|\mathbf{x_{ij}}\| \geq d_1 > d$, force is zero. d and d_1 are preconfigured parameters. This control strategy suits every robots in this chained network, and each robot is only affected by the neighbor robots belongs to one triangle.

Suppose a translation and rotation to the double-layer chained network is performed, which rotates by φ first, then followed by a translation by (x_t, y_t). For each point p in the triangle in Fig. 6 as an example, the new position p' is defined as below:

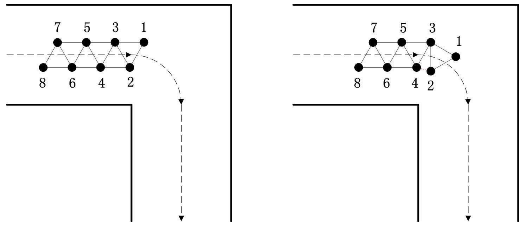
$$p' = Tp = \begin{pmatrix} x\cos\varphi - y\sin\varphi + x_t \\ x\sin\varphi + y\cos\varphi + y_t \\ 1 \end{pmatrix}$$

with T the 3×3 matrix. We prescribe a trajectory of the double-layer chained network and parameterize by $s: T(s)$, so $p'(s) = T(s)p$. And besides translation and rotation, we could expand and contract our double-layer chained network by adjusting the communication range d to βd, where β is the variable for adjusting.

B. In Constrained Environment

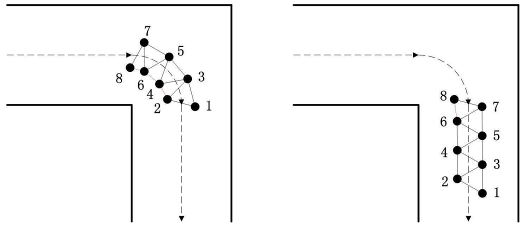
In real application, mobile sensor networks are mostly used in some unknown environments, in which have interference and obstacles. Our control algorithm is capable of overcoming these problems and adjusting its chained formation.

Fig. 7 shows the process of double-layer chain tethering in a bounded environment. The laser scanner equipped on the mobile robot can detect the distances between the robot and its left side, right side and front bound. When the bound is detected, as Fig. 7(b) shows, the leader would judge the surroundings in advance. The comprehensive information can yield virtual forces and rotate the first triangle. We divide the double-layer chain into outer-layer and inner-layer according to its rotation. In Fig. 7(c), the leader robot turns right, so node(1), (3), (5) and (7) make up of the outer-layer, and other nodes make up of the inner-layer, vice versa. The inner-layer links would contract its length, which means the distances between node(n) and ($n \pm 2$) do not match normal communication range d, but a variable distance βd. We set the variable $\beta \in [0.5, 1]$ to avoid collision, which depends on the curvature of current case. When the curvature of the leader robot is less than a certain threshold, the double-layer chain is going back to the straight hallway, as Fig. 7(d) shows. Then the inner-layer would recover and extend the node distances to the communication range d. For different curvature, the sequence of transmitting nodes and interference range of communication R should be calculated accurately.



(a) Double-layer chain is moving in a hallway.

(b) Double-layer chain is turning at a corner.



(c) The ideal formation for making a turn

(d) Double-layer chain finishes turning

Fig. 7. Double-layer chain tethering in a constrained environment

C. Fault Tolerance

In unknown environment, it is common to encounter some situations, *i.e.* node death, which could break the communication links. When it happens, the double-layer chain tethering could drive neighbor robots to cover the gap and retain the connection. In order to achieve this capability, a heart beating message is sent into the network from the source node in every short time span. If every node in the double-layer chain network, (except the source and next node), receives the message twice, the network is in a good state; if any node receives it only once, then there must be a error in the network.

As Fig. 8 shows, node($n-1$) is lost. When node(n) sends a message M to the network, node($n-2$) can hear it, but can't node($n-1$). At next time slot, node($n-1$) can not forward M to its neighbor, so node($n-2$) and ($n-3$) receive nothing next slot. Then node($n-2$) only receives the message from source node(n) but can not from ($n-1$). The network would detect the loss and node($n+1$) can be driven to fill the gap and retain the communication link. The nodes following

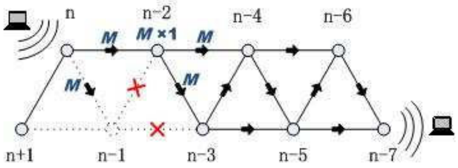
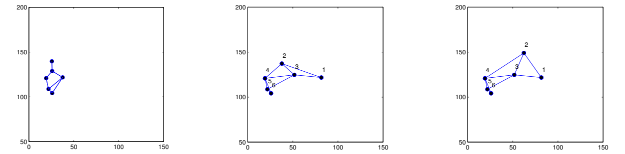


Fig. 8. Link broken in double-layer chain communication

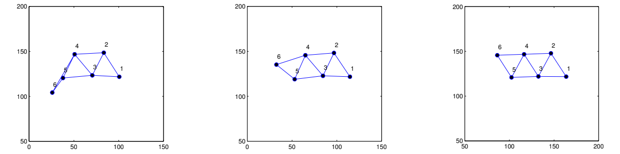
node($n+1$) would move forward to maintain the double-layer chained network.

V. EXPERIMENTS

A simulation for double-layer chain tethering in an open environment is developed in MATLAB. The results testify the effectiveness and adaptability of our decentralized control algorithm.



(a) The initial deployment (b) The snapshot after 4s (c) The snapshot after 6s



(d) The snapshot after 12s (e) The snapshot after 16s (f) The final snapshot after 20s

Fig. 9. The simulation snapshots of double-layer chain tethering in an open environment

The simulation of double-layer chain tethering executed in an open environment is shown in Fig. 9. After initial deployment (9(a)), a robot is selected to be a leader of the chain. Every time a robot moves, *e.g.* node(1) in Fig. 9(b), it finds the closest neighbor (node(3) in the figure) as its fixed neighbor with the same method as single-layer chain tethering. Then this fixed neighbor would calculate the distances to its last neighbor and the lead robot of its neighbor. In Fig. 9(b), node(2) would calculate the distances to node(3) and node(1), then virtual forces can drive node(2) to the place where within the same communication threshold of both node(3) and node(1), as Fig. 9(c) shows. Similarly, other nodes would do the same transform and finally in Fig. 9(f), a double-layer chain is formed.

This tethering gives more stable and robust structure than single-layer chain tethering. According to its advantages, double-layer chain tethering is preferable for constrained environment with unpredictable information. Hence, double-layer chain tethering in a constrained environment is our focus for future research. The deployment could encounter some obstacles or bounded environment with our adaptive multi-robot control algorithm. Also the communication protocol should be considered in carefulness due to the impact from changeable formation.

VI. CONCLUSIONS

A decentralized robotic cooperation algorithm is proposed in this paper. A comprehensive metric is introduced for evaluating the communication links quality in order to find the optimal communication range for mobile network. Based on the control algorithm, single-layer chain tethering and double-layer chain tethering are defined for open and constrained environment. Virtual forces which composed of repulsive forces and attractive forces, are produced to drive the robot to a stable position with the capability of avoid obstacles and bound. Simulation results show the feasibility and adaptability of our proposed control algorithm.

REFERENCES

[1] J. Jennings, G. Whelan, and W. Evans, "Cooperative search and rescue with a team of mobile robots," in *International Conference on Advanced Robotics*, pp. 193–200, July 1997.

[2] W. Burgard, M. Moors, C. Stachniss, and F. Schneider, "Coordinated multi-robot exploration," *IEEE Transactions on Robotics*, vol. 21, pp. 376–386, June 2005.

[3] K. Martinez, J. K. Hart, and R. Ong, "Environmental sensor networks," *Computer*, vol. 37, no. 8, pp. 50–56, 2004.

[4] J. hwan Kim, D. han Kim, and Y. jae Kim, *Soccer Robotics*. Springer-Verlag New York, LLC, 2004.

[5] C. Dixon and E. W. Frew, "Maintaining optimal communication chains in robotic sensor networks using mobility control," in *International Conference on Robot Communication and Coordination*, pp. 1–8, 2007.

[6] C. Dixon and E. Frew, "Controlling the mobility of network nodes using decentralized extremum seeking," *IEEE Conference on Decision and Control*, pp. 1291–1296, Dec. 2006.

[7] K. Luthy, E. Grant, and T. Henderson, "Leveraging rssi for robotic repair of disconnected wireless sensor networks," *IEEE International Conference on Robotics and Automation*, pp. 3659–3664, April 2007.

[8] J. Tan, "A scalable graph model and coordination algorithms for multi-robot systems," *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pp. 1529–1534, July 2005.

[9] E. Stump, A. Jadbabaie, and V. Kumar, "Connectivity management in mobile robot teams," *IEEE International Conference on Robotics and Automation*, pp. 1525–1530, May 2008.

[10] M. Ma and Y. Yang, "Adaptive triangular deployment algorithm for unattended mobile sensor networks," *IEEE Transaction Computer*, vol. 56, no. 7, pp. 946–847, 2007.

[11] A. Das, J. Spletzer, V. Kumar, and C. Taylor, "Ad hoc networks for localization and control," in *Proceedings of IEEE Conference on Decision and Control*, vol. 3, pp. 2978–2983, Dec. 2002.

[12] P. Ogren, E. Fiorelli, and N. Leonard, "Cooperative control of mobile sensor networks:adaptive gradient climbing in a distributed environment," *IEEE Transactions on Automatic Control*, vol. 49, pp. 1292–1302, Aug. 2004.

[13] S. Bansal, R. Shorey, and A. Kherani, "Performance of tcp and udp protocols in multi-hop multi-rate wireless networks," *IEEE Wireless Communications and Networking Conference*, vol. 1, pp. 231–236, March 2004.

[14] H. Lundgren, E. Nordströ, and C. Tschudin, "Coping with communication gray zones in ieee 802.11b based ad hoc networks," in *Proceedings of the 5th ACM international workshop on Wireless mobile multimedia*, pp. 49–55, 2002.

[15] W. Ye, J. Heidemann, and D. Estrin, "Medium access control with coordinated adaptive sleeping for wireless sensor networks," *IEEE/ACM Transactions on Networking*, vol. 12, pp. 493–506, June 2004.

[16] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," in *Proceedings of the 2nd international conference on Embedded networked sensor systems*, pp. 95–107, 2004.