The Design and Implement of Acoustic Array Sensor Network Platform for On-line Multi-target Tracking

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Abstract—**We present the design, implement and evaluation of a sensing platform for on-line multi-target tracking based on acoustic array networks, named Integrated Acoustic Array Sensor Network Tracker (IAASNT). To provide on-line multi-target tracking service, a well-designed system structure is proposed, composed by supporting components and associations between each part. Among these, IAASNT's multi-level low-power management and integrated tracking frame set it different from other related platforms. The integrated tracking frame is the core of the system and has been carefully designed, to achieve a self-acting tracking service. Finally, a series of experiments on system have been done to evaluate the performance of IAASNT. The tracking experiments on system show a perfect tracking performance in both noise-free and noisy environment, and the tracking precision can be within 5.8m in 300*300m area.**

Keywords-acoustic array networks; system design; integrated target tracking; low-power management; tracking experiments

I. INTRODUCTION

Target tracking attracts much attention for its great application in military, scientific and civil. Since the past decades, the related theory has achieved great development and many target tracking systems have also been developed. In applications, especially in military application, however, active sensors like radar are easily detected, located and destroyed by enemies. So this kind of system does not fit for this special application. As passive sensor technique and wireless sensor networks (WSN) develop, passive sensor networks provide a new era for target tracking and acoustic array sensor networks is a nice try among these. However, for lacking of study in a system view on this fields and the limitation of processing capacity on sensors, little work has provided an integrated on-line tracking service under acoustic sensing platform. We make efforts to achieve a sensing platform for on-line multi-target tracking based on acoustic array sensor networks.

Figure 1 shows a typical acoustic array sensor networks for target tracking application. Several sensor array nodes locate in the area. When a target occurs, the sensor nodes can get measurements about target motion such as bearing measuring by utilizing the phase difference between array elements. Then measurements will be uploaded to the data fusion center and target tracking estimation can be obtained here. Sometimes, a feedback structure is needed to transfer some important information from fusion center to sensor nodes as necessary instructions.

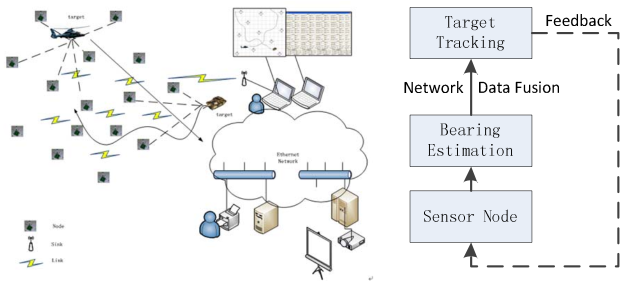

Figure 1. Typical acoustic array sensor network

In this paper, we present the design, implement and evaluation of Integrated Acoustic Array Sensor Network Tracker (IAASNT), a platform for on-line multi-target tracking. Each sensor node in IAASNT is developed by embedded system and can get the bearing estimation by sampling and processing acoustic signal from targets. Comparing with the classical tracking system such as radar, acoustic array sensor network systems have advantages including passive measuring is low-power consuming and well stealthy, and network frame can achieve more general and robust service. IAASNT's advantages also lies on its well-designed system structure and the implement of supporting components in the structure. Among these, components for integrated target tracking and multi-level low-power management are the highlights of the system distinguish it from other related systems. The challenge in designing the tracking component is how to combine classical tracking model and the supplement for the special characteristics in this system and the integrated tracking frame we proposed gives a feasible solution. Based on this frame, we do efforts on modules such as initial state estimation combining with track initiation, node selection. To evaluate the performance of system, we perform experiments on tracking.

Our IAASNT system is a nice try for the target tracking application in WSN including innovations both in theory and practice. The contributions mainly lie on the following points:

- Firstly, the system structure of IAASNT is well-designed and a series of approaches are proposed for components in this structure. All these work can be easily referenced by scientists and engineers to construct similar systems.

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- Secondly, IAASNT has realized on-line multi-target tracking with relatively high precision, which is a great challenge to tracking systems in acoustic sensing systems, especially in acoustic array sensor networks.
- Finally, many experiments have been arranged to test the performance of the system and from which practical experience and theory are well combined.

This paper is organized as following. Section 2 discusses the related work on acoustic sensing system. Section 3 describes the system structure of Integrated Acoustic Array Sensor Network Tracker and components in this structure. Section 4 introduces the tracking experiments and analysis. Finally, Section 5 summarizes the system and gives the future work.

II. RELATED WORK

In this section, we give an overview on related acoustic target sensing platforms. The design of acoustic target sensing platforms attracts much attention from academe, industry and military. A number of projects have been accomplished by research institutes. Acoustic ENSBox [3] and VoxNet [4] designed by Grid etc. are distributed acoustic sensing platforms based on ARM. The work is mainly on self-localization by using of acoustic range and bearing estimation. Another famous work done by UCLA is acoustic sensor networks for woodpecker localization [5]. By using several acoustic arrays which consists of four microphones, the platform can get the bearing estimation of each array by running AML algorithm and location estimation by running LS algorithm. The design and implement of this platform is simple but it provides a general frame for target localization based on acoustic array sensor networks. UCLA has also developed a microphone array network by using of iPAQ3760s which achieves the localization of acoustic target [2]. In this wok, practical coherent array processing issues are considered, including the propagation noises and time synchronization. This platform builds a totally distributed sensor network structure within which virtual array substitutes traditional array and it provides new direction for WSN on tracking. In an integrated sensing platform done by UCB achieves multi-target tracking by taking advantages of co-processing acoustic, vibration, visual and other signals [1]. The well-designed system architecture makes it possible for different sensors to work cooperatively. Also, in military applications, many projects have been done such as gunfire localization system [6] and intrusion detection system [7] based on acoustic monitoring. U.S. Army Research Laboratory has done lots of work in this field. A robot-based acoustic detection system was developed to detect and localize on impulsive noise events [8]. Along with some helmet-mounted acoustic array labeled by soldiers, the whole system can produce an accurate location of a target.

As a summary, acoustic target sensing platforms have been developed for target detection, localization and tracking. Most of the previous work is for single-target and real time tracking service can be hardly provided. IAASNT, however, is designed for on-time multi-target tracking. Also, it provides an integrated tracking service which has rarely been considered in acoustic array sensor networks in a system view.

III. PLATFORM OVERVIEW

The IAASNT system provides an integrated on-line multi-target tracking service. To achieve the goals, we design a novel system structure as shown in Figure 2. The structure consists of 3 layers including application layer with target tracking component, middleware layer with communication, synchronization, signal process and node localization components, hardware layer with hardware of sensor node for and a cross-layer with low-power component.

On the basis of the hardware of sensor node, signal process and communication components achieve basic function of sensor network, that is sensing and data transmission. Then node localization and time synchronization components realize a practical sensing system for providing determinate position and time. All the above supporting components make tracking service to be a simple multi-input multi output (MIMO) model. In addition, a multi-level low-power management is also one of the most meaningful works in this system.

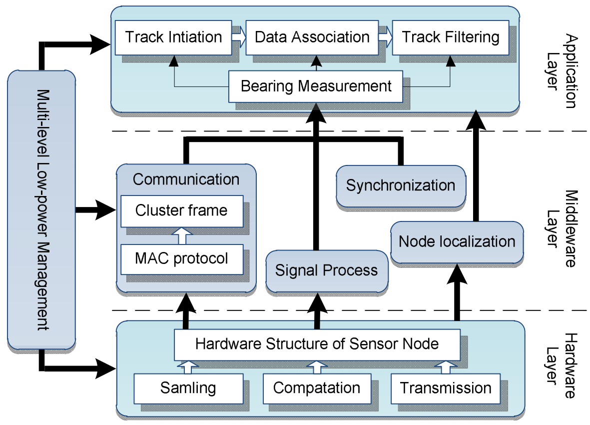


Figure 2. Multi-layer system structure

A. *Hardware Layer*

The hardware of node consists of three parts: acoustic array, power supply module and processing module. Acoustic array is made up of 4-channel or 6-channel microphones laid out in an circle and the azimuth angle is defined in a uniform regulation. The node is powered by a Li rechargeable battery. Regulator circuit and voltage conversion circuit are designed to provide stable +/-12V voltage for sampling chip and +/-5V voltage for other chips.

The processing module, shown as Figure 3, is based on MSP430, FPGA and DSP. FPGA as the master device mainly perform the following tasks: 1) producing the timing of the signal sample (AD); 2) controlling the wireless module to complete the transmission of information; 3) controlling the wireless module and self-localization module to complete synchronization and self-localization; 4) providing some necessary expansion interface, to facilitate the function of the system expansion and system upgrading. As the core device of signal processing, the main function of DSP is to run the core algorithm and provide application service, such as target tracking and localization. The communication between FPGA and DSP is based on the data bus and address bus. Some memory devices, such as SDRAM and Flash are also mounted on the bus to be used in the intermediate results storing. MSP430 is the MCU in the IAASNT system which achieves low-power work mode.

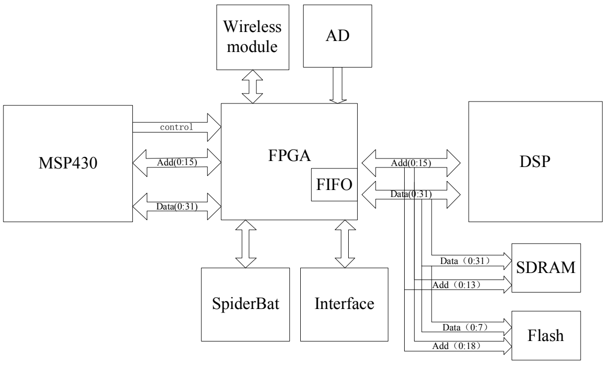


Figure 3. Structure of node processing module

B. Middleware Layer

The components in middleware layer are the link between hardware layer and application layer. To provide real-time bearing measurements for tracking service, signal process, communication and synchronization are necessary and are achieved in node. Node localization is executed when system is deployed and is done in fusion center.

Signal process is mainly responsible for accomplishing Direction of Arrival (DOA) estimation. DOA estimation has been studied for decades and in our system, a method named Focusing Khatri-Rao subspace method (FKR) [9] is proposed based on coherent signal-subspace method (CSM) and Khatri-Rao (KR) subspace. FKR includes two primary steps: focusing and arrangement. After focusing, the DOAs are estimated according to the property of KR product.

For simplify, communication follows the basic protocols for WSN but we make a modification into the MAC layer packet structure, named Q-MAC [10], to achieve adjustable bandwidth communication. In Q-MAC, superframe structure and support multi-hop packet transmission are adopted, see Figure 4. The first byte of the packet payload is a load indicator variable which indicates the number of current queued packets in the node's MAC layer. Receiving the data packets, thus receiving the indicator variable, the cluster head knows the senders' packet load by extracting the indicator variable from the data packet. It then accordingly allocates certain TDMA slots into the next superframe period to compensate the queued packets of the son-devices. To give a chance of knowing scattered traffic loads of all son-devices, a fixed length CSMA period follows the variable TDMA period.

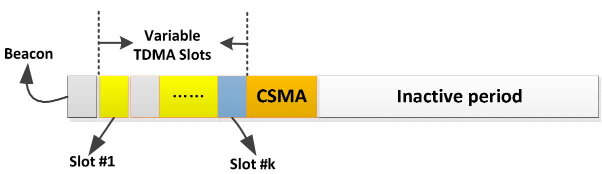


Figure 4. Superframe sturcture

Time synchronization is necessary for application platforms. In order to synchronize nodes, we design a lightweight scheme as following. All nodes are synchronized by sink node. The sink node broadcasts a synchronization message with MAC-layer timestamp and seqNum every 10 seconds. The nodes in the broadcast radius of sink node collects reference point and then broadcast a synchronization message. By this way, all the nodes can collect reference point directly from the sink node or indirectly. By this scheme, the network can be synchronized from sink node to the normal nodes within 1ms difference.

Node Localization is also an important component for tracking. Different from the traditional node localization, node localization in IAASNT needs to decide not only the position but also the orientation of node. A special mechanism is designed to accomplish the task [11]. During processing, a moving media-object passes through the monitoring area so that each node can sense the media-object and report its bearing measurements. In the meantime, the position of media-object is obtained by GPS. By using bearing measurements of nodes and the position of media-object, node localization can be easily achieved by maximum likelihood algorithm and the cost function can be written as:

$$Cost = \sum_{i=1}^{N} \frac{1}{\sigma_i^2} \left(\theta_i - \arctan \frac{p_{y_i} - y}{p_{x_i} - x} + \beta \right)^2 \qquad (1)$$

Here, p_{x_i}, p_{y_i} is the position of media-object and x, y is the position of node to be localized. θ_i is the bearing measurement of node, and β is the orientation which is also an unknown parameter to be determined. σ_i^2 is the variance of measurement error.

C. Application Layer

The application layer concerns with data processing on target tracking and an integrated tracking frame is designed as shown in Figure 5. The frame designed for IAASN includes modules such as tracking filtering, data association, tracking initiation similar to the classical tracking frame, but also includes modules such as node selection, initial state estimation designed since multi-sensor and bearing-only measurement bring in new problems.

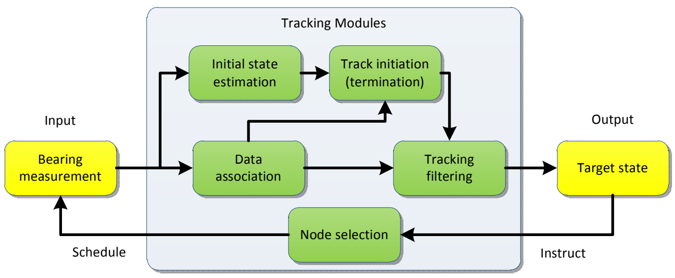


Figure 5. Integrated target tracking frame

The classical modules for tracking follow the common algorithms such as interacting multiple model (IMM) algorithm [12] for filtering, joint probabilistic data association (JPDA)

[13] for data association. For the limitation of the paper size, the details are omitted and we emphasize on introducing node selection and initial state estimation parts.

Node selection for target tracking consists of two main parts: establishing a cost function for weighing localization accuracy and optimizing the cost function to obtain node selection strategy. Node selection under bearing only measurements is quite different from common node selection in WSN for the cost function is quite difficult in this case. The geometrical dilution of precision (GDOP) [14] is a fine cost function in theory and many related works have been done based on it. The difficulty mainly lies on the searching process to optimize the cost function which is a NP-hard problem. Instead of complex process for an optimal or suboptimal node selection result, IAASNT uses a simple heuristic approach similar to the "add one node at a time" method [15] to achieve an acceptable result, see Algorithm 1. Firstly, neighboring nodes are selected as candidates. Then, by finding the minimizing cost function $f_{\cos t}$ proposed in [15], the first selected node into Ns is obtained. By finding one node minimizing cost function each time, node selection process can be accomplished. Although it is not an optimal approach, the method can achieve a relative fine result in a short time which meets the requirement for on-line process.

Algorithm 1 Node Selection: heuristic approach

Input: the position of all the nodes Na , the predicted target position Xt and covariance Pt , the expected number of node selection $num(Ns)$

Output: node selection output Ns

find min($2num(Ns)$, $num(Na)$) neighboring nodes $\{Nr_i : 1 \le i \le num(Nr)\}$ to predicted target position from Na ;
for each Nr_i , $i = 1,...,num(Nr)$ **do**
  calculate $f_{\cos t,i}(Nr_i, Xt, Pt)$;
end for
select Nr_k from Nr for minimize $f_{\cos t}$ as the first node of Ns ;
for $j = 2,...,num(Ns)$ **do**
  find the minimize $f_{\cos t}$ by Ns and Nr_j from each Nr_i not in Ns ;
  $Ns = Ns \cup Nr_j$; $f_{\cos t} = f_{\cos t,\min}$;
end for

Initial state estimation is needed on tracking initiation for under bearing only measurements the initial state is not ready for us. The problem of initial state estimation is in fact multi-target localization under bearing only measurements. Single target localization under bearing measurements is not difficult while multi-target localization algorithm is rare. In fact, it is almost impossible to absolutely distinguish target and ghost in only one scan under measurement suffering undetected and false-alarm. We design an integrated mechanism in which initial state estimation part is responsible for providing a probability based initial state estimation but leaves more precise work to the target initiation part during several scans' iteration, as shown in algorithm 2. In initial state estimation part, a probability is calculated while localization to give a relative division of targets and ghosts which is decided by the residual between the predicted azimuths and the bearing measures. Then, by setting a distance taboo, only a few relatively independent localization outputs are selected and new tracks to be initiated are created based on the localizations and their probabilities. The reason why we choose only one scan to estimate initial state is that measurements from targets may be not stable and localization results are not accurate enough so it is hard to estimate a valid target velocity by using multiple localization from multiple scans. In order to avoid the influence on lacking of initial velocity estimation, covariance of target motion noise should be set larger at first. In track initiation part, probability-based algorithm similar to [16][17] is adopted. Probability of target existence updates while iteration and tracking initiation strategy can be made based on it.

Algorithm 2 Initial state estimation and track initiation

Input: measurements $\mathbf{Z} = \{z_i(j)\}$ received from each node, record for track to be confirmed $\mathbf{TraIni} = \{TI_i\}$

Output: record for track confirmed $\mathbf{TraCon} = \{TC_i\}$

$Loc = \varnothing$, $P_{Loc} = \varnothing$;
for each group consists of 3 neighboring sensors **do**
  [Loc , P_{Loc}]=MultiLocalization($\mathbf{Z}$);
end for
do LocMerge on [Loc , P_{Loc}] ;
create new track TI_i to $\mathbf{TraIni}$ by [Loc , P_{Loc}];
for each TI_i from $\mathbf{TraIni}$ **do**
  $TI_{i,k+1}$ =TrackIteration($TI_{i,k}$);
  if $TI_{i,k+1} \to \mathrm{P}_{TarPro} \le \mathrm{P}_{TarTer}$ **then**
    delete TI_i from $\mathbf{TraIni}$;
  else if $TI_{i,k+1} \to \mathrm{P}_{TarPro} \ge \mathrm{P}_{TarCon}$ **or** supplementary condition **then**
    add TI_i to $\mathbf{TraCon}$, delete TI_i from $\mathbf{TraIni}$;
  end if
end for

D. Low-power Management

Low-power management technique is a necessary part for an applied system especially for wireless sensor network system. The main idea of low-power management is scheduling nodes to work in active mode only when necessary. In order to achieve reliable service with low-power consuming, a multi-level low-power management is proposed for IAASNT as shown in Figure 6. The management can be divided into three levels corresponding to the multi-layer structure of system and we will describe them in bottom-up flow.

In hardware level, the design and implement of sensor node satisfies the basic regulations for low-power consuming. Also, the hardware structure makes it possible for the node to change its mode according to decisions made by upper levels to achieve energy saving.

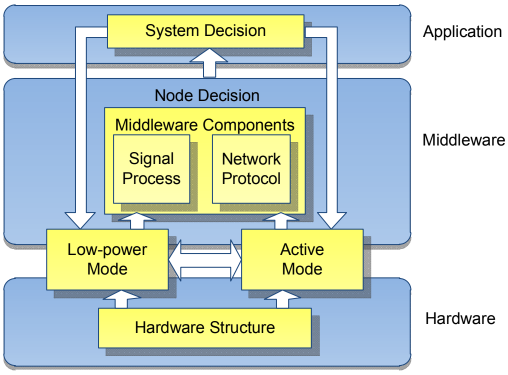


Figure 6. Multi-level low-power management frame

In middleware level, low-power mode is designed for signal process component and also mode transition strategy is proposed. For signal processing, the calculation for DOA estimation needs to be executed by DSP which is high power consumption relatively. So low-power mode is designed with DSP shut down to save energy and only low power consuming MSP430 is working to make decisions for mode-transition. The comparison of power consumption for the two modes is as shown in Table 1. The decision is made by a single node without any knowledge of other nodes. In detail, by calculating the correlation coefficient of the data in frequency domain from any two array elements, a relatively credible conclusion can be made on whether the target exists or not. In order to keep a relatively stable detection, a mechanism similar to Schmitt Trigger is utilized to avoid too many transitions which will lead to heavy system cost for scheduling and confusion on system. Also, the proposed low-duty network protocol can work well under different modes and achieves further energy saving.

TABLE I. POWER CONSUMPTION FOR TWO MODES

Mode\device	DSP	FPGA	MSP430	others	total
Active	1.23w	0.31w	0.05w	0.78w	2.37w
Low-power	0	0.31w	0.05w	0.2w	0.56w

In application level, the process for service can be divided into two stages, these are target-finding stage and target-tracking stage. Strategies are designed for the two stages respectively to make system decision for scheduling nodes, see Figure 7. In target-finding stage, due to limitation of node sensing and lacking of a global view for tracking service, decisions made in node level may be not reliable enough, which will lead to delay or mistake in target finding. So the main challenge lies on problems of dealing with node undetected. A group neighboring cooperation strategy is proposed to solve the problem. The node detection decisions are reported to fusion center and detection nodes are grouped according to their positions. If the number of nodes in group is more than 2, nothing else needs to do. Otherwise, neighboring nodes of the group will be set active so that the number of active nodes in group reaches 3 which is necessary for initial state estimation in tracking. While in target-tracking stage, information from nodes is redundant and strategies in system level are made to reduce the redundancy both in time and space in order to achieve more energy saving. The scheduling is based on the result of node selection module in target tracking component.

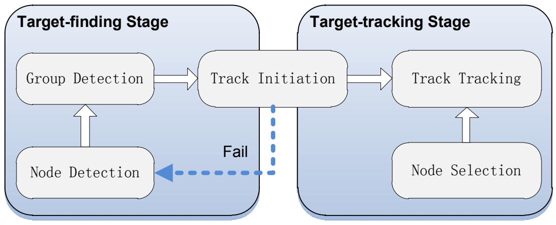


Figure 7. Low-power management in system level

IV. EXPERIMENTS AND ANALYSIS

We have performed a number of experiments to evaluate tracking service of IAASN in two environments: single target tracking in noise-free environment and multi-target tracking in noisy environment.

A. Noise-Free Environment Experiment

The noise-free experiment [18] is performed in an open area more than 1000*1000m. Five sensor nodes are randomly disposed on the flat glass ground about 300*300m, see Figure 8. The real position of each node is obtained by GPS device. In order to test node localization component, an assistant object with GPS moves through the area and it is easy to localize each node. Figure 9 shows the result of node localization comparing with the real position.

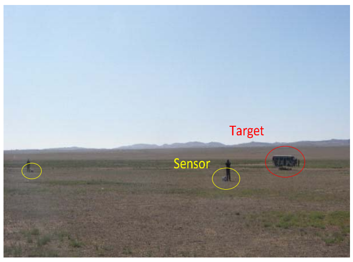


Figure 8. Field for experiment in noise-free environment

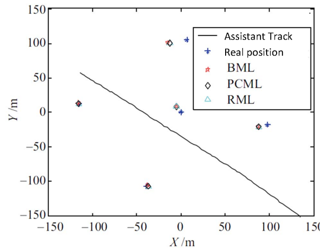
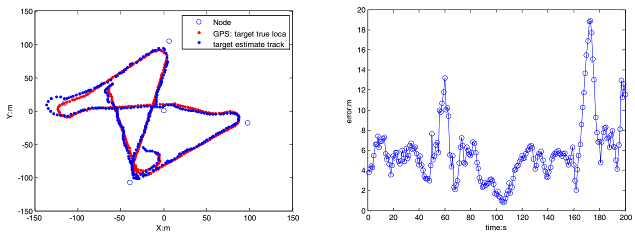


Figure 9. Nodes deployment and localization



(a) (b)

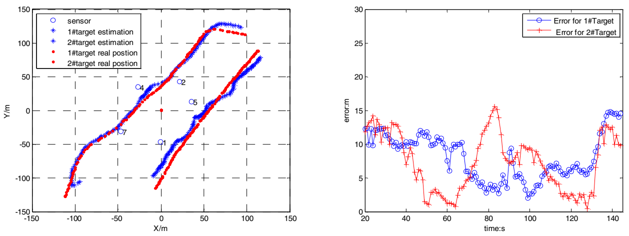
Figure 10. Comparison of estimate and real track: (a) track plot (b) error

For testing performance of target tracking, we put a GPS device on target and get the ideal target position in real time. The target moves around each node and we get the estimated target track and the real track in the same time, see Figure 10(a): the red point denotes the ideal target position obtained by GPS and the blue point is the estimated track obtained by this system. The error analysis is shown as Figure 10(b). The average error is about 5.8m. Considering that the target is about 5m long, the tracking performance is perfect.

B. Noisy Environment Experiment

In application, more complex case must be considered. To test the performance, we do experiment in a noisy environment [19]. In this experiment, the field available is only about 300*300m and the sensors are deployed relatively closely.

In this experiment, we do multi-target tracking test. Two vehicles are moving in the experiment field at the same time. Figure 11 (a) shows the tracking result (blue point) comparing with real position (red point) and (b) is the error analysis. The average errors for two targets are about 8.1m and 7.3m respectively. Figure 12 shows the initial state estimation when target starts moving and in this time four potential tracks are ready for initiation. Figure 13 is the probabilities of target existence for the two tracks which have been successfully initiated. Track 1# (blue line) can be quickly initiated for the probability of the track exceeds initiation threshold within 3s. While the probability of Track 2# (green line) increases slowly, under the help of supplement strategy, it is also initiated within 6-7s. Also, it can tolerant bad measurements and even undetected in some degree, see Track 2# at about 105s.



(a) (b)

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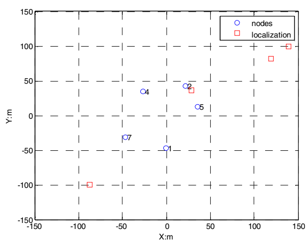

Figure 12. Initial state estimation for track initiation

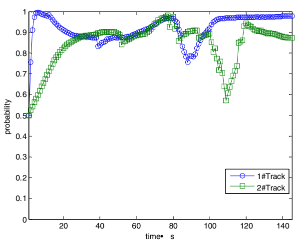

Figure 13. Calculation for probability of track

V. CONCLUSION

Research in WSN for tracking has been active in the past ten years. Most of the works faces difficulties on real-time processing and multi-target problems. While in IAASNT, the designing of system structure and the implement of each component makes it possible to provide an integrated on-line multi-target tracking service which can rarely be seen at present. It is a significant work from other similar systems. Also, the experiments show a fine performance of the system. However, there are still problems to be solved in the future. Besides algorithms mentioned above, the design of low-cost and low-power sensor is a great challenge. Also, theoretical and experimental study for problems under large-scale of sensors is not yet sufficient which will be the future work.

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