RFID-enabled tracking in flexible assembly line

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Abstract Radio frequency identification (RFID) technology provides a wireless means to detect and identify objects. By using RFID reader as detecting sensor, an RFID-assisted object tracking system is developed to track the object movement for a flexible manufacturing assembly line. Both range-based and range-free cooperative object tracking algorithms are analyzed for the system. And to achieve tradeoff between the reader plate's density and cost, only simple readers with omnidirectional aerial are considered in this article. To further enhance the assembly line efficiency, a particle filter model is developed to further process the object tracking results to improve the tracking accuracy. The proposed tracking system can also forecast the movement state of objects in the assembly lines.

Keywords RFID · Assembly line · Tracking · Particle filter

1 Introduction

Radio Frequency Identification (RFID) is a technology capable of providing wireless identification of objects. The basic units of any RFID-based systems are RFID tags and RFID readers. An RFID tag is used to attach to an object to enable the information about that object to be transmitted to the interested parties via an RFID reader. Such a real time and wireless means of information exchanges between tags and readers enables emerging innovative applications in many areas, such as logistics, supply chain management, manufacturing, warehouse managements, etc.

With this real-time object tracking capability, RFID provides a potential mean to flexible manufacturing assembly lines. An assembly line is generally considered as a manufacturing process in which a product is created by composing interchangeable parts as scheduled. Past assembly line usually uses robotic vision technologies to recognize and control the robot's end of arm tooling to pick and place objects. In this design, we provide an alternative method for object locating on assembly line with identification capability. Every object in the assembly line shall be attached with a passive RFID tag in advance and turned into a so-called smart object. Their movement states could then be tracked and traced to help in facilitate real-time planning and control for manufacturing assembly line. For example, tags could be mounted at regular intervals in the assembly line, with readers covering the entire working region resulting in a sensor network for the assembly lines.

The location of a tag could then be picked up anywhere in the assembly system. When the tagged object is or passes within effective range of an RFID reader, the reader could pick up its information to further estimate the object's position and processing steps. In this way, it is possible to track objects in an assembly line, where an accurate position of an object is often a valuable information asset. The object tracking capability in assembly line would eventually improve the assembly line operation efficiency.

This object tracking capability is more valuable in environments where the to-be-assembled objects are randomly placed in the assembly line, resulting in their irregular positions and movement paths. And, it is especially fit for hybrid environment where different kinds

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of objects are mixed together in the assembly line and required to be pick and placed individually to increase machine flexibility, such as applications on a flexible machining and assembly system or on a dock assembly. To better detect the object position and movement path in an assembly line, an RFID-assisted object tracking system is developed in this paper. The core of the system is the object tracking algorithm with filtering capability to enhance its tracking performance. It is expected that this system could be used for automating the assembly lines through enhancing the monitoring and controlling capabilities of the manufacturing assembly processes.

Organization of this paper is as follows. In Section 2, a literature review is provided, and the motivation of the paper is given. The RFID-assisted object track system for assembly line is described in the Section 3. In Section 4, a convex model is applied as the basic range-free object locating algorithm. And in Section 5, the particle filter method is applied to the object tracking system to increase the locating accuracy and predict the object's moving trend. Section 6 introduces the implementation of the system and Section 7 is the performance evaluation of our proposal. Section 8 will conclude this paper.

2 Literature review

There have been researches focused on object tracking or locating techniques literatures in automating manufacturing applications. Most of the existing work is mainly based on camera-based surveillance, image processing, and RADAR-based technologies.

Most existing solutions are based on vision-guided robotic system that can operate on a moving assembly line. Articles [1, 2] developed distributed control architecture with vision inputs of multilevel accuracy. The architecture for the proposed system is subsumptive and hierarchical. Each control loop can add to the competence level of the loops below, and they can present a coarse-to-fine gradation with respect to vision sensing. At the coarsest level, the processing of sensory information enables a robot to become aware of the approximate location of an object in its field of view. On the other hand, at the finest end, the processing of stereo information enables a robot to know more precisely the position and orientation of an object in the coordinated frame of the robot. And article [3] employs a Hough transform technique to determine the translations and rotations of overlapping parts in the image. RFID technologies can provide alternative solutions to these questions.

Snake-based algorithms are used to implement dynamic snakes to track moving objects in sequences of images [4, 5]. Active contours, or snakes, are computer-generated curves that move within images to find object boundaries. They are often used in image analysis and computer vision to detect and locate objects and to describe their shape.

Article [6] considers an augmented reality interface for guiding manual assembly. They present a framework for assembly scene augmentation that is based on robotic assembly planning and studied the problem of sensing for augmented reality without the use of fiducials. It developed a formulation that combines model- and appearance-based approaches for recognizing assembly states.

In the RADAR-based systems, some existing locating algorithms are already developed and applied in object tracking, such as the range-based and range-free locating techniques [7]. The range-based methods mainly include RSSI, TOA, TDOA, AOA, etc. Sensors used in these environments can detect the distance, direction, velocity, and certain attributes of the object with certain accuracy. And the control center can make use of the collected message to locate the object accurately. The range-free-based methods include gravity, convex, DV-HOP, amorphous, APIT, etc. are usually used in low-cost environments. The sensor used is quite simple and cheap and without the capability to detect object accurately. They can only decide whether the object appears in their monitored region and cooperatively calculate out the object's position to achieve the tracking function.

In these object or object tracking methods in the RADAR systems, filter methods are applied to further improve the tracking accuracy. Thus, the original locating results will be further processed via these filters. Research in [8] reported an analysis of the particle filters on online nonlinear/ non-Gaussian Bayesian tracking in detail and introduced an application method for it. The particle filter estimates the object state from observations obtained by detectors and provides statistical information necessary to configure the detectors. Research in [9, 10] provided an evaluation of a Kalman filter. Its input data were subjected to significant statistical preprocessing. In [11, 12], it is reported that for the fixed sensor, the particle filter performs significantly better than an Extended Kalman Filter.

To summarize, the existing object tracking or object locating proposals are mainly based on computer vision analysis or RADAR's range analysis. And other methods like GPS- and GPRS-based object tracking [17] obviously are not applicable in manufacturing assembly lines. With the increasingly cheaper RFID reader and tags, RFID-based and sensor network-based tracking techniques can be an applicable solution for object tracking in assembly lines. We have seen proposals to apply RFID to detect objects' identities in the assembly lines to help make informed decision in the manufacturing processes (e.g. [18, 19]). In our previous paper [20], a new solution for object tracking in assembly line based on a set of readers to form a RFID

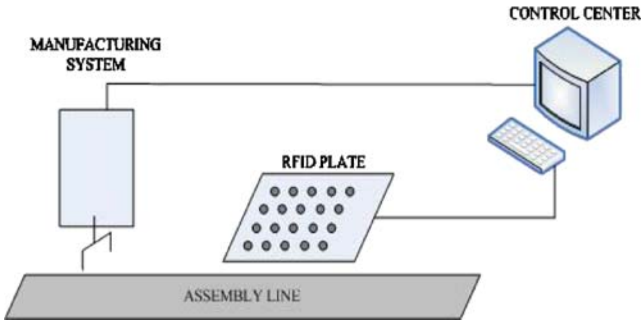


Fig. 1 Structure of the auto-control manufacturing system

grid is proposed. Based on the architecture, we evaluate the tracking algorithms and the system efficiency in detail in this work. The readers with or without the distance detection capability are used as sensors in the grid to detect object passing through their monitored region. To decrease the total cost of the system, only the simplest and cheapest readers with omnidirectional aerials are considered in our system. A range-based triangulation algorithm and a range-free convex model are used as examples in our design to cooperatively track the objects in the assembly line. And in order to further enhance the tracking accuracy and predict the object's moving state, a particle filter is used to reprocess the tracking result. We contribute to the state of arts of researches on flexible manufacturing assembly lines by deploying an RFID grid in the assembly lines to (1) detect objects presence, (2) track the objects movements, and (3) predict the objects' positions.

3 Object tracking assembly line

In order to get more accurate current and forecast location of objects in the assembly line, RFID technology emerges to be a promising yet cost effective mean to be used in such a flexible manufacturing process. The RFID-assisted object tracking system helps to locate the object in an assembly line and improves decision making as regarding to when and where to process the working objects in the assembly lines. The conceptual framework of the object tracking assembly line is shown in Fig. 1. As implementing any real-life manufacturing solutions has profound and enormous impacts in its battlefield operations, it is not easy to experiment the proof of the concept in a real-life assembly line to avoid unnecessary disturbances to its busy schedules. And a real-life product assembly line usually has more complexity and difficulty without necessarily helps gaining useful insights. Instead, the case should simulate such a real-life environment as far as possible and which can help us to focus our attention and achieve better understandings about these questions without being buried in a complicated manufacturing problem itself. We utilize simulated implementation in this work and which can be safely adapted to different manufacturing applications such as in car production line, flexible assembly system, and other real-life pilot cases as generalized in articles [21] and [22].

The system will have to first deploy certain amount of RFID readers with aerials to proper places along the assembly lines in a factory. This will establish a few monitoring plates. All these RFID readers interconnected wired or wirelessly and forming an RFID grid as the working plate to detect, identify, and track moving objects in the assembly lines. Each item will be attached with a passive tag in advance. When these smart objects pass the working region of the monitoring plates, information in the tags can be retrieved within proper communication range. Through analyzing the information exchanged among tags and readers, the position of the object in the assembly line can be evaluated.

The object tracking system for the assembly line is set up as follows. The whole object tracking system components include RFID tag, RFID reader, assembly line, and control center of the auto-control manufacturing system. The structure of the system is shown in Fig. 1.

An RFID monitoring plate consisting of RFID readers and tags can be added to the existing auto-control manufacturing system in the assembly line in Fig. 1. The plate can detect and send the tracking results to the control center. The structure of the plate is shown as Fig. 2.

In order to achieve balance between the locating accuracy and the cost of tracking function, we must carefully estimated the density of sensor readers in the monitoring plate based on the capability of readers. For the mass readers monitoring plate, using complicated and powerful readers will greatly increase the total manipulating cost. Here, we only considered the simple and cheap readers accompanied with omnidirectional aerials.

To evaluate the position of tag in the monitoring region, the tag must be detected simultaneously by more than one reader to increase accuracy, which decided the least density of readers in the plate. In our approach, the plate is equally

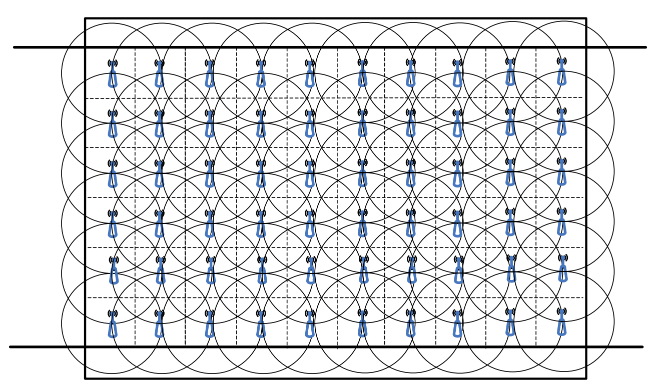


Fig. 2 Tracking system in assembly line

divided into 60 rectangles. In the center of each rectangle is equipped with a reader with the communication range equal to the wide of the rectangle to guarantee the basic density and accuracy. The detailed evaluation is given in the next section.

Consequently, this RFID network grid establishes a monitoring work plate region on the assembly line. Each object with an RFID tag attached moving through this region will be detected by the readers. As the attached tag usually contains a unique ID, the object can be uniquely identified and located in the assembly line.

Multiple readers may receive the tag's signal and record its identity when a tag moves into the monitored region. By collecting all the detection results, the control center can estimate the location of the object by comparing the reported readers' location. And as multiple tags can be read simultaneously, we can track multiple objects on the same time. The design of monitoring plate can be decided according to the true communicating distance and the scale of the plate in different applications.

Besides tracking objects in this system, we can further take advantage of the nonlinear Bayesian tracking method to forecast the object's moving direction and location on the next time interval by recursively calculate the prior probability density function (pdf) of the tag's position in the region. And based on these forecasting results, the automatic manufacture system can fine tune and coordinate its tools as to when and where to pick and process the object.

4 Object tracking approach

In today's RFID applications, the reader usually equips with an omnidirectional or directional aerial to communicate with tags. The function of these aerials is limited, often emphasizing on solving the communication problems between readers and tags. By introducing certain algorithms, we can realize new applications based on the simple hardware.

This section introduce a cost-effective approach to deploy an RFID-based sensor network, for example, RFID grid is used to identify, track, and predict object's movement in the assembly lines. There have been a lot of investigations reported in object tracking in sensor network research. Some of the existing locating algorithms can be ideally introduced into RFID-based object tracking applications. As mentioned in Section 2, these methods can mainly be divided into range-based and range-free locating algorithms.

4.1 Range-based locating algorithm

Range-based algorithm can help the detector to locate target through measuring the distance or angular between points, these algorithms mainly include RSSI, TOA, TDOA, AOA, etc. In our tracking system in assemble line, the reader act as anchor node which position has already known. Then, we wish the tag-attached object be located by these anchors.

Tags can work as RF transmitter devices. But readers are not designed for distant and direction detection usually. Reader with such detection functions is expensive currently and not suitable for massive aggregated application. And here, we only assume the use of cheap readers with omnidirectional aerial which at acceptable cost and can only detect the distance between reader and tag. Because such reader shall be simple enough to achieve the request of low cost, we do not expect that it can detect the direction or with high accuracy. By geometry knowledge, we take the two-dimensional metric to represent the reader plate in the case and use the triangulation method to calculate the position of target. As shown in Fig. 3, point can be located by the intersection of three or more circles with known position readers as the center.

By geometry knowledge, we take the two-dimensional metric to represent the reader plate in the case. A point can be located by the intersection of three or more circles with known position readers as the center.

In Fig. 3a, let the center point $C_i=[x_i,y_i]^T$ represent the position of reader i; d_i represent the distance between reader i to the target tag. We can get a set of detecting results: $[C_1, d_1]^T,\ldots,[C_M,d_M]^T$. $M\geq 2$ is the sample number. Let $X=[x,y]^T$

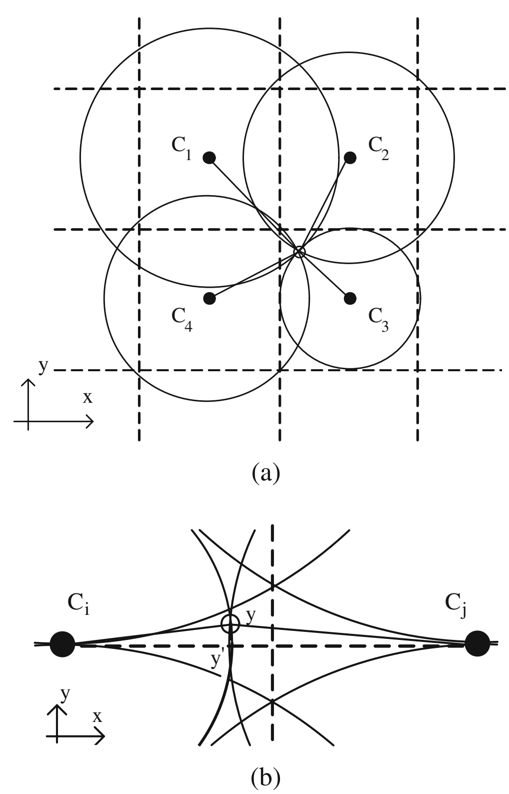


Fig. 3 Trilateration diagram

be the point of intersection of circles, which can be calculated through the following array:

$$\begin{cases} (x_1 - x)^2 + (y_1 - y)^2 = d_1^2 \\ (x_2 - x)^2 + (y_2 - y)^2 = d_2^2 \\ (x_3 - x)^2 + (y_3 - y)^2 = d_3^2 \\ (x_4 - x)^2 + (y_4 - y)^2 = d_4^2 \end{cases}.$$

And further generate the common conclusion:

$$X = \frac{1}{2}\left(A^T A\right)^{-1} A^T b \tag{1}$$

Among which:

$$A = \begin{bmatrix} (x_1 - x_4) & (y_1 - y_4) \\ (x_2 - x_4) & (y_2 - y_4) \\ (x_3 - x_4) & (y_3 - y_4) \end{bmatrix}$$

$$b = \begin{bmatrix} x_1^2 - x_4^2 + y_1^2 - y_4^2 + d_4^2 - d_1^2 \\ x_2^2 - x_4^2 + y_2^2 - y_4^2 + d_4^2 - d_2^2 \\ x_3^2 - x_4^2 + y_3^2 - y_4^2 + d_4^2 - d_3^2 \end{bmatrix}$$

Once we get the distance measure result from reader, and as the position of reader have already known, we get A and b. Consider the rows of array A is equal or bigger than columns, the tag's position X can be worked out.

In Fig. 3b, the actual detecting samples may be two when target moves into the small middle area between readers and may be one when it locates in the border of the plate. For the former occasion, we can either increase the density of readers in the plate with the rise of cost or use the middle point of the two point of intersection of circles as estimated result with possible down grading of accuracy. For example, we use y' substitute y in Fig. 3b to restrict hardware cost with certain accuracy lost. And the evaluation result is shown in Section 7. For the later occasion, we can cut off the inaccurate area around the border of plate in the assembly line to guarantee $M \geq 2$.

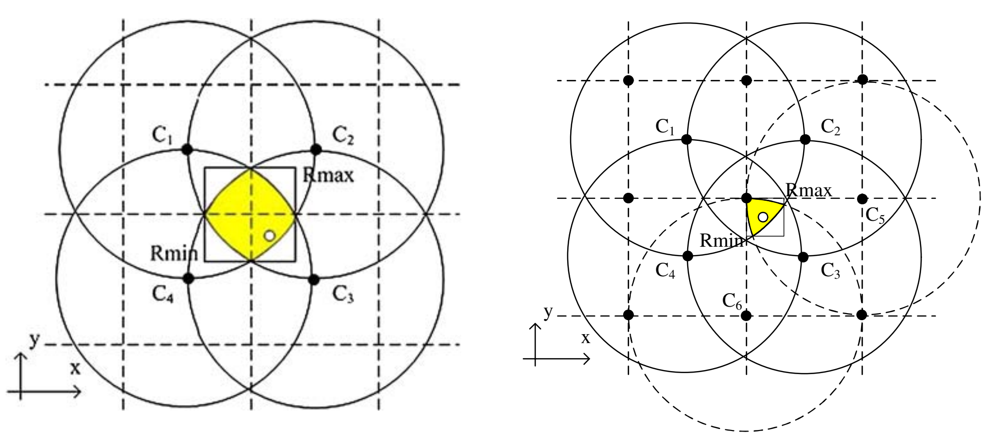
Furthermore, the measurement of distance can be affected by many factors. If a large and dynamic margin of error is not an option, the detection options should be seriously considered, like IR, ultrasonic, and other RF solutions to calculate position.

4.2 Range-free locating algorithm

As most cheap RFID equipment are not sophisticated enough to provide such value-added functions as distance, direction, and other attributes such as detection, the range-free tracking algorithms seem to be another good candidate to fulfill our requirements by considering the structure of our assembly line tracking system and the characteristics of the RFID readers.

Range-free positioning mechanism requires only simple reader and has great advantage in terms of cost. Although single reader can only decide whether any tag appears in its detecting region, certain tracking accuracy can be achieved by using redundant information from appropriate network density and position fusion algorithm. These features make it particularly suitable for large-scale applications. As mentioned in Section 2, several range-free locating algorithms are considered in our approach. After carefully evaluation, the convex-based locating algorithm [6] is chosen for it fits well with our assembly line scenarios.

When several readers detect the appearance of a tag simultaneously, the range-free convex method calculates the region of intersection (ROI) of the monitoring region of readers at first. Then, we consider the region's center of gravity as the object's location $L_{target}(x', y')$. As shown in Fig. 4a, we can draw a locating rectangle according to the maximum and



(a) $N_{detect}=1$ (b) $N_{detect}=2$

Fig. 4 Locating rectangle diagram

minimum coordinates of the region, which can be represented as Rmax(Xmax, Ymax) and Rmin(Xmin,Ymin).

We use N_{detect} to represent the number of readers located in each grid. It represents the density of readers in the plate. In Fig. 4a, a reader is put in the middle of each grid. If only one reader can detect tag, the center of the locating rectangle equal to the position of the reader. But with certain density, we can guarantee $N_{\text{detect}}>1$ in most situations. And as shown in Fig. 4b, the ROI is obviously reduced if the reader density is doubled to two readers per grid. Every point of grid is equipped with a reader in Fig. 4b. As we can see directly from the figure, the higher the density is, the smaller the ROI is, and we can get higher accuracy.

The control center needs to calculate all the points of intersection for these readers based circles to get ROI. To enhance the tracking accuracy, we can increase the density of reader in the plate. After some readers report their detecting results to the control center, it can calculate Rmax and Rmin based on the positions of the readers.

For example, let $X=[x,y]^T$ be the point of intersection of circles $C_i=[x_i,y_i]^T$ and $C_j=[x_j,y_j]^T$ with fixed radius r, we can get the equation:

$$X=\frac{1}{2}Ab \tag{2}$$

$$A=\begin{bmatrix}(x_i+x_j) & -(y_i-y_j)\\(y_i+y_j) & (x_i-x_j)\end{bmatrix}, b=\begin{bmatrix}1\\ \pm\frac{\sqrt{r^2-l^2}}{l}\end{bmatrix}$$

$$l=\frac{1}{2}\sqrt{(x_i-x_j)^2+(y_i-y_j)^2}$$

By judging whether X is in the locating rectangle, we can adjust Rmax and Rmin. Smaller the area of locating rectangle is, higher the tracking accuracy is. The control center recursively calculate all the points of intersection to decide the coordinates of the region. Then, we can get the object's location as:

$$L_{\text{target}}\left(x',y'\right)=\left(\frac{x_{\max}+x_{\min}}{2},\frac{y_{\max}+y_{\min}}{2}\right) \tag{3}$$

5 Tracking enhancement

Many problems in science require estimation of the state of a system that change over time using a sequence of noisy measurements made on the system. As the object may be randomly put on the assembly line and/or the original tracking results are usually irregulars caused by the measurement noise and the random movement of the object, the tracking results usually cannot satisfy the accuracy request for precise manufacturing.

To increase the tracking accuracy and improve the efficiency of manufacturing system, we can recursively amend the estimated tracking result x by the measurement result z. Bayesian filter method is a good choice to realize this function and has been widely studied in RADAR systems for the traditional target tracking applications. To solve the nonlinear problems with measurement noise in the set of measurement sequence, we have to develop a nonlinear Bayesian tracking model at first. To solve the nonlinear Bayesian model, we then have to apply the particle filter methods for increasing the tracking accuracy and building object location forecast model. Here, we concentrate on the state-space approach to model the dynamic assembly line systems, and the focus will be on the discrete time formulation of the problem. The dynamic-state estimation information in the tracking depends on the kinematics characteristics of the target [13–15].

5.1 Nonlinear Bayesian tracking

To define the problem of tracking in nonlinear Bayesian tracking, consider the evolution of the state sequence $\{x_k, k\in N\}$ of an object and the measurements $\{Z_i, i=1,\ldots,k\}$. Then, the tracking problem is to recursively calculate some degree of belief in the state x_k at time k. The posterior pdf $p(x_k|z_{1:k})$ may be obtained recursively in two stages: prediction and update [7].

Supposing the $p(x_{k-1}|z_{1:k-1})$ is available, the prediction stage obtaining the prior pdf of the state at time k via the Chapman–Kolmogorov equation:

$$p(x_k|z_{1:k-1})=\int p(x_k|x_{k-1})p(x_{k-1}|z_{1:k-1})dx_{k-1} \tag{4}$$

This equation describes a Markov process of order one. At time step k, a measurement z_k becomes available, and this may be used to update the prior pdf via Bayes' rule:

$$p(x_k|z_{1:k})=\frac{p(z_k|x_k)p(x_k|z_{1:k-1})}{p(z_k|z_{1:k-1})} \tag{5}$$

Where the normalizing constant is as follows:

$$p(z_k|z_{1:k-1})=\int p(z_k|x_k)p(x_k|z_{1:k-1})dx_k \tag{6}$$

Depending on the likelihood function$p(z_k|x_k)$, the measurement z_k is used to modify the prior density to obtain the required posterior density of the current state. The recurrence relations 4 and 5 form the basis for the optimal Bayesian solution. This recursive propagation of the posterior density is only a conceptual solution. In general, it cannot be determined analytically. Thus, we apply particle filter method to solve this problem.

5.2 Particle filter in object tracking

The particle filter method is a technique for implementing a recursive Bayesian filter by Monte Carlo simulations approach. It is now extensively used to solve sequential Bayesian inference problems arising in econometrics, advanced signal processing, or robotics. The method approximates the sequence of probability distributions of interest using a large set of random samples, named particles. These particles are propagated over time using simple importance sampling and resampling mechanisms.

Particle filter is a useful method for handling the time series problems of object tracking, where the reader models and object dynamics are often non-Gaussian and/or nonlinear. Particle filter takes a series of weighted particles from the current system state at first. Based on these particles, it estimates and updates the next state of the system to calculate the pdf of objects. Then, we can use the estimated prior pdf to predict the object's location at the next time interval. This will help to prepare the readers and other equipment in advance. We would evaluate performance of the particle filter based on existing tracking data.

Our application of particle filter method includes three steps: initialization, prediction, and update. The detailed descriptions of them are as follow:

1. Initialization: In particle filter method, the continuous monitoring region can be decomposed in to N_s particles, $\{x_i,\ i{=}1,\ldots,N_s\}$. The density of particles is set according to the requirement of accuracy. We use x_i represent the center of particle i, use $z^{(t)}$ denote the measurement position in time t, and the measurement history up to time t is denoted as $\overline{z^{(t)}} = \{z^{(0)}, z^{(1)}, \ldots, z^{(t)}\}$. There is no measurement before object move in the area and the pdf of each particle is equal to $p\left(x_i^{(0)}|z^{(0)}\right) \equiv p\left(x_i^{(0)}\right) = 1/n$. N is the number of particles in the detected region. Then, the posterior pdf at t can be written as

$$p\left(x^{(t)}\middle|\overline{z^{(t)}}\right) \approx \sum_{i=1}^{n} w_{t|t}^{i}\delta\left(x_t - x_t^i\right) \tag{7}$$

Here, $\delta()$ is the Dirac delta measure.

2. Prediction: In the prediction phases, the prediction equation is shown as:

$$p\left(x^{(t+1)}\middle|\overline{z^{(t)}}\right) \approx \sum_{i=1}^{n} w_{t+1|t}^{i}\delta\left(x_{t+1} - x_{t+1}^i\right) \tag{8}$$

And the weight of the particle x_i can be represented as:

$$w_{t+1|t}^{i} \triangleq \sum_{j=1}^{n} w_{t|t}^{j} p\left(x_i^{(t+1)}|x_j^{(t)}\right) \tag{9}$$

$p\left(x^{(t+1)}\middle|x^{(t)}\right)$ is related to object kinetics model. In practice, the exact object dynamic is rarely known. According to our initial analysis of assembly line's dynamics, we assume that the object has a speed uniformly distributed in [0, $v_{\max}$] to simplify the illustration. To further simplify the model, the object heading is also assumed uniform in [0,2π]. Therefore, $p\left(x^{(t+1)}\middle|x^{(t)}\right)$ is a disk centered at $x^{(t)}$ with radius $v_{\max.}$ Under this model, the predicted belief $p\left(x^{(t+1)}\middle|\overline{z^{(t)}}\right)$ is obtained by convolving the old belief $p\left(x^{(t)}/\overline{z^{(t)}}\right)$ with the uniform circular disk kernel. The convoluting reflects the dilated uncertainty about object location due to motion.

3. Update: After getting the prior pdf of the particle and the measurement $z^{(t+1)}$, we can calculate the weight of each particle as

$$w_{t+1|t+1}^{i} \approx \frac{w_{t+1|t}^{i} p\left(z_{t+1}\middle|x_{t+1}^{i}\right)}{\sum_{j=1}^{n} w_{t+1|t}^{j} p\left(z_{t+1}\middle|x_{t+1}^{j}\right)} \tag{10}$$

and update the posterior pdf at t+1 as

$$p\left(x^{(t+1)}\middle|\overline{z^{(t+1)}}\right) \approx \sum_{i=1}^{n} w_{t+1|t+1}^{i}\delta\left(x_{t+1} - x_{t+1}^{i}\right) \tag{11}$$

To simplify the tracking system model, we can further assume that the measurement result z is geometry distribution in a circle area with the radius $v_{\max}$[16]. The process of particle filter is as Fig. 5.

6 Implementation

To apply the method, we described on the last section on assembly line, an RFID grid as shown in Fig. 2 should be deployed at first. We also have to tag all the working objects to be assembled in advance. When the object on assembly line moves through the monitored region, the tag on the object can be activated and send its ID to the readers within the communication range. The signal could be received by multiple readers according to the object's and the reader's position. And based on the reader's position, we can estimate the object's position with range-based or range-free algorithms mentioned in Section 4. After the monitoring plate detects and sends the tracking result black to the control center with certain frequency, the model can adjust the posterior pdf $w_{t|t}$ for each particle in time interval t.

{* Input: *} $p(x^{(t)} \mid \overline{z^{(t)}}), z^{(t+1)}$

{* Output: *} $p(x^{(t+1)} \mid \overline{z^{(t+1)}})$,

Var $x^{(t)}$: estimated location at time interval t

$z^{(t)}$: detected location at time interval t

n : particle number

PF $(p(x^{(t)} \mid \overline{z^{(t)}}), z^{(t+1)})$

Begin

For i=1:n do

$$w^{i}_{t+1|t} \overset{\Delta}{=} \sum_{j=1}^{n} w^{j}_{t|t}\, p(\overline{x}^{(t+1)}_{i} \mid \overline{x}^{(t)}_{j})$$

End for

For i=1:n do

$$p(z^{(t+1)} \mid x_i^{(t+1)}) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x_i^{(t+1)} - z^{(t+1)})^2}{2\sigma^2}}$$

$$w^{i}_{t+1|t+1} \approx \frac{w^{i}_{t+1|t}\, p(z^{(t+1)} \mid \overline{x}_i^{(t+1)})}{\sum_{j=1}^{n} w^{j}_{t+1|t}\, p(z^{(t+1)} \mid \overline{x}_i^{(t+1)})}$$

End for

$$p(x^{(t+1)} \mid \overline{z^{(t+1)}}) \approx \sum_{i=1}^{n} w^{i}_{t+1|t+1}\, \delta(x_{t+1} - x^{i}_{t+1})$$

return $p(x^{(t+1)} \mid \overline{z^{(t+1)}})$

End

Fig. 5 The process of particle filter

And considering the kinematics characteristics of the object, we can calculate the prior pdf $w_{t+1|t}$ for each particle for the next time interval $t+1$. Furthermore, we can also predict the object's location by collecting the prior pdf of all the particles, and this information could be used in arranging the manufacture procedure.

7 Performance evaluation

Manufacturing assembly lines have certain requirements such as the lead time and accuracy to detect and track the objects in order for the machine tools to respond in a timely and precise manner. In this section, we evaluate the detection efficiency of our object *tracking* approach for assembly lines. In order to test the effect of particle filter method to the tracking system, we simulate an object moving through a monitored region of 3×5 m^2 along a tangent curve and with the max speed of 0.15 m/s. Sixty readers with omnidirectional aerials and with the communication range as 0.5 m are deployed in the assembly line as shown in Fig. 2. Only those particles with the weight above 10^{-8} are calculated, and the rest are neglected. Considering the 0.1 x0.1 m^2 grid, we can get the tracking result as Fig. 6.

The cloud in the figure represents the prior pdf of the object. The dashed line represents actual track of the object. The black line represents the original tracking result of the system through a range-free convex-based tracking mechanism. And the green line in the figure represents the filtered tracking result. From this figure, we can see that after the processing using particle filter, the tracking result appears more smoothly. The average track error decreases from 0.24 to 0.22 m. The prior pdf of object mainly depends on its velocity. It can represent the movement state of the object. Based on the tracking and forecasting result, this technology can be used in a lot of auto-manufacturing

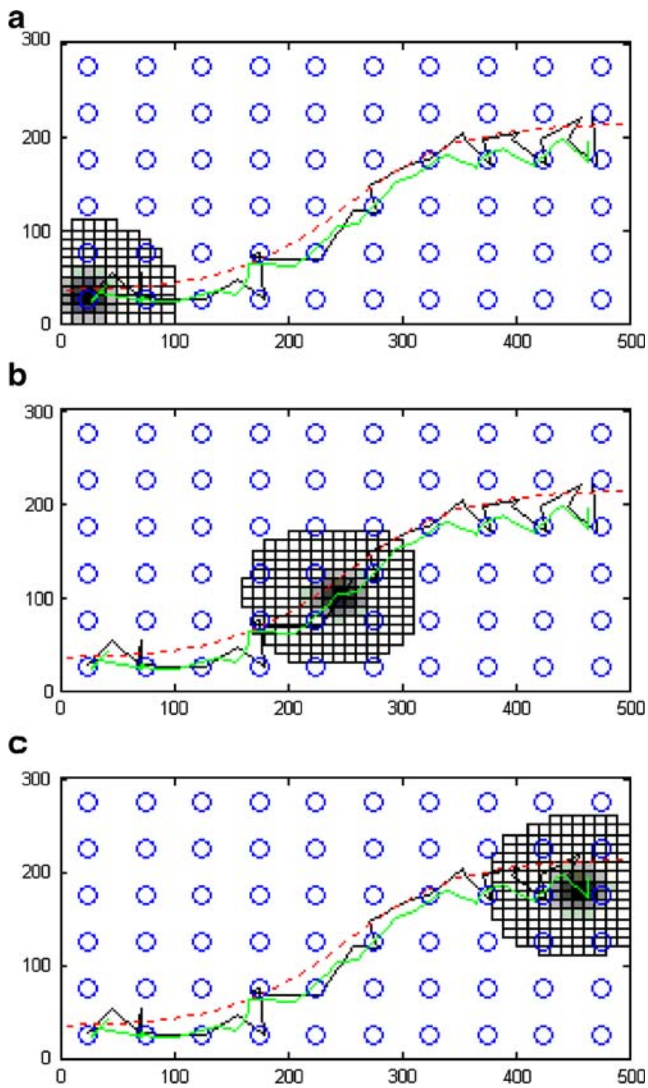


Fig. 6 Three tracking steps in a particle filter scene

applications "on-the-fly," such as lug nut securing, stamping, wheel decking, glass decking, etc.

To further test the track error, both range-based and range-free detecting mechanisms introduced in the article are evaluated.

Figure 7 is the test result of range-based tracking according to Section 4.1. As the detected result of reader's distance may be affected by environment, we consider the effect of detected error to the triangulation in this test. The horizon coordinate depict the average detecting error with noise. The figures show the average track error and filter record against the reader's detecting error in 20 tests for each point. From the test result, we can see that the accuracy of range-based location is highly dependent on the capability of reader.

After using particle filter, the tracking error of triangulation locating can be efficiently decreased. We can further enhance the tracking accuracy of the system.

Figure 8 depicts the tracking result's accuracy of range-free convex algorithm according to Section 4.2. With the increasing number of readers' N_{detect} in each grid, more nodes may detect the tag and take part in locating activity. Then, the tracking error between estimated position and actual position decreased slightly. And according to Fig. 6, particle filter can narrow down the level of error effectively.

As these tests have shown, the range-based location generally performs better than range-free location. But with the increasing of the reader's detected error in the fixed communication range, the range-based locating method loses its advantage gradually. And taken into consideration with the total cost of the locating system, range-free locating methods can be a good choice in many applications.

Finally, we try to change the density of particle filter grid to observe the impact to tracking precision. Table 1 shows two sets of filter results in different grid width, the left column records the original range-free convex tracking result, the middle column is the filter result with 10 x10 cm^2 grid, and

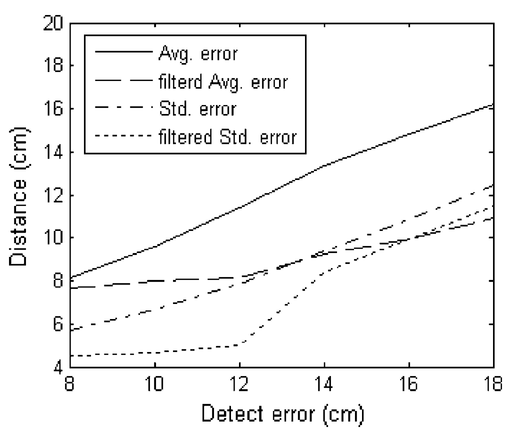


Fig. 7 Range-based triangulation tracking error against detected error

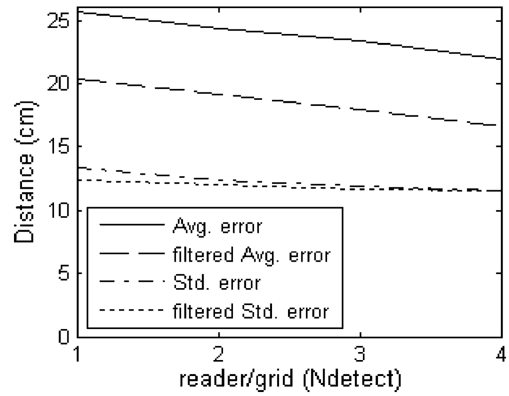


Fig. 8 Range-free convex tracking error against N_{detect}

the right column is with 5 x5 cm^2 grid. After comparing the columns, we can see that with the increasing grid density, the locating precision after filter can be slightly improved. But such improvement is at the cost of great increase of computation complexity. The grid density should be carefully chosen according to the computation capability of control center when applying this method in real applications.

8 Conclusion

In this paper, we propose and analyze RFID-enabled object tracking techniques for flexible manufacturing assembly lines. In the flexible manufacturing system, smart objects attached with tags can be identified and located in the work plate where RFID reader grid is equipped to form a monitoring region. The improved accuracy of the object tracking and lead time for preparing the robot's end of arm tooling would effectively improve the manufacturing processes. The method provided in our approach can also be widely applied to other auto-control applications, such as delivery center, cargo, airport, etc., where different kind of items need to be handled on the same transport track.

The readers in the grid are used as sensors to detect object passing through their monitored region. A range-based triangulation algorithm and a range-free convex algorithm are used in our design to cooperatively track the objects in the assembly line. In order to further enhance the

Table 1 Contrast of two particle filters (cm^2)

	Convex	Particle filter	
		10×10	5×5
Avg. error	25.19	17.85	16.45
Std. error	13.25	10.4	10.6

tracking accuracy and predict the object's moving state, a particle filter is used to reprocess the tracking result to predict the objects' position. To calculate the nonlinear models, a few assumptions are made to simplify the dynamics model of the assembly lines in this paper. There exist rooms to improve the modeling of kinetics of the objects in the assembly lines, which would potentially lead to higher tracking accuracy. Of course, methods to help obtain the calculation results in a bounded time period are also needed for more complicated kinetics models.

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