POSE ESTIMATION OF CONSTRUCTION MATERIALS USING MULTIPLE ID DEVICES FOR CONSTRUCTION AUTOMATION

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Abstract: This paper describes a method of pose (position and orientation) of large object such as construction materials using multiple ID devices for construction automation. Object pose is crucial issue for construction automation, however, the pose can change by the robots and workers that do not have ID reader or measure the object pose. The proposed method supposes the position and direction of each ID device with respect to the object coordination frame and those of the ID reader with respect to the reference coordination frame. The paper focuses on the simplification of the estimation model to apply the method to the real environment. Experimental results show feasibility of our proposed method.

Keywords: parts oriented construction system, data collection and labeling system, radio frequency identification (RFID), and pose estimation.

1. INTRODUCTION

It is a crucial issue for building the relation ship between states of the construction materials at the construction site and their information such as their existence, pose (pose and orientation), forms, task information for workers or robots, and so on, for efficient construction automation [1]. One of the methods for building the relationship is using ID devices, for example, radio frequency identification devices and barcodes [11][12]. Several studies using ID devices attached to the construction materials have been introduced, for example, tracking of the construction materials at the construction site [2][3][4], tracking of the tools for the workers [5], and scheduling of the construction site including the production of the construction materials [6].

This paper describes a method of the pose (position and orientation) of the construction materials using multiple ID devise to maintain the relationship between the status of the materials and their information. Object pose is important status for construction tasks; however, the object pose can be changed by the workers or robots that cannot update the data of the object. In this case, the workers and robots should measure the object pose. The proposed method estimates the object pose using at least two ID devices attached to the object.

The paper focuses on the simplification of the pose estimation and the geometrical condition of the ID devices using pose estimation. Several pose estimation method of the construction materials. Furlani has been proposed pose estimation using at least not aligned three RFID devices based on the device position with respect to the object coordination frame [7]. Umetani has been proposed pose estimation using at least two ID devices attached to the different sides of the object based on the device position and orientation with respect to the object coordination frame [8].

Former one is not considered to the motion planning of the ID reader because the method does not apply the orientation of the ID reader. On the other hand, the latter one uses the full orientation of the ID device. It is difficult to register the orientation of the ID devices.

This paper shows feasibility of the proposed method through the modeling result of the pose estimation and experimental results. The paper introduces integration of the objects such as the construction materials and their information using ID devices. We show the method for estimation of the object pose based on acquisition of the multiple ID from the ID devices attached to the object. Experimental results show feasibility and effectiveness of the method.

2. OBJECT-POSE ESTIMATION USING ID DEVICES

This section describes a method of object-pose estimation using ID device attached to the large object such as the construction materials. First, we introduce the integration of objects at the construction site and their information using ID devices. Then, the section illustrates the object pose using ID devices to maintain the relationship between the objects at the site and their information.

2.1 Integrated management of objects and their information using ID devices

The recent advancement of information and communication technologies has brought the integrated management of objects and their information using ID devices. Figure 1 shows the concept of the intelligent environment using ID devices at the construction site for building the relationship. Using the ID devices, workers and robots can obtain the

information of the construction materials by obtaining the IDs of the devices attached to the materials using their ID readers. Then, the workers or robots can achieve tasks using the information using acquisition of the ID attached to the objects.
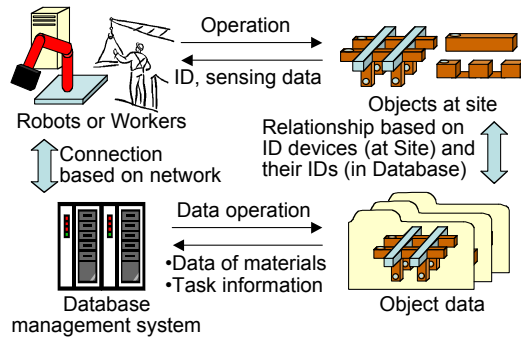

Figure 1: Integration of objects at the construction site and their information using ID devices.

The integrated management of the status of the objects and their information is applied to various situations in robotics and automation fields, for example, navigation in the environment [10], a manipulation task [1]. Using the ID devices, the workers or robots can identify the objects easily and perfectly, since the ID of the device is unique in the environment. The workers or robots updates the information stored in the database using the relation between the objects in the site and the information in the database since the database server can search the information that should be updated easily.

It is required to maintain the relation ship between the status of the materials and their information to realize integration of the construction materials with their information using ID devices. It is required that the status of the construction materials at the construction site is identical with that of the information of the construction materials in order to realize the integration. If the stored information in the database conflicts with the status of the materials at the site, the workers or robots cannot obtain the correct information using the ID devices. Therefore, the integrated management of the construction materials and their information using ID devices ends in failure. In this case, the workers and robots should acquire the status of the materials using their equipments and update the information of the materials stored in the database.

2.2 Object-pose estimation using ID devices

The pose of construction materials is important status for the workers and robots to achieve the tasks. However, the construction materials can be moved by the workers or robots that cannot update the information of the materials using the ID device. As a discussion in the former subsection, the object pose should be estimated by the workers and robots at the construction site. In addition, it is difficult to estimate the pose of the large object directly

using the measurement equipment such as the fixed cameras at the site since the range of the cameras is narrow so that the large environment is required.

We propose a method of estimation of object pose (position and orientation) using multiple ID devices. The method estimates the object pose using the acquisition of the ID of the devices attached to the object and the relative movement of the ID reader. The assumption of the method are described as follows:
- The object size is much larger than the communication area of the reader.
- Multiple ID devices are attached to each object.
- The position and orientation of the ID reader with respect to the reference coordination frame can be measured accurately
- The position and direction of each ID device with respect to the object coordination frame are registered in the database.
- The proposed method does not conflict the assumption of the conventional updating method for the information of the construction materials.

In the following sections, we define the geometrical model of the ID reader and the device when the ID reader acquires the ID of the device attached to the object. The properties of the method are described using the derived geometrical model of the ID acquisition. In addition, the paper illustrates the pose estimation experiment. Modeling results of the pose estimation and experimental results show feasibility of the proposed method.

3. MODELING OF OBJECT POSE ESTIMATION USING MULTIPLE ID DEVICES

This section describes a method of object-pose estimation using multiple ID devices. The method supposes that the position and orientation of the ID reader can be measured on acquisition of the ID. The section introduces the geometrical relation between the ID reader and the device. Then, the section shows that the object pose is estimated using at least two ID devices attached to the object.

3.1 Geometrical Condition of ID reader

First, we define the geometrical condition of the ID reader and the device on acquisition of the ID. We suppose a commercial small RFID reader as an ID reader in the paper. The ID reader has small communication area. In addition, the object size is much larger than the size of the communication area. The properties of the ID reader are described as follows:
- The ID reader has a communication area along the axis of the reader as shown in figure 2.
- The ID reader can acquire the ID of the device if the ID device is in the communication area of the ID reader and the device directs to the reader. The ID reader has the range of the inclination of the device to the reader.

- The ID reader can acquire the ID of the device even if the device rotates about the axis of the direction of the ID reader.

Figure 2 shows the model of the ID reader and ID device on acquisition of the ID. $\Sigma_{R,D1}$, $\mathbf{p}_{c,D1}$, $R_{\Omega D1}$, $\mathbf{p}_{o,D1}$ and $\mathbf{k}_{o,D1}$, indicate the coordination frame of the ID reader, position of the device with respect to the reader coordination frame, the device position with respect to the object coordination frame, rotation with respect to the reader coordination frame, the device position with respect to the object coordination frame and the device direction with respect to the object coordination frame, respectively. The size of $\mathbf{k}_{o,D1}$ is 1. The reader direction is set to the z-axis of the reader coordination frame. The range of $\mathbf{p}_{c,D1}$ and $R_{\Omega D1}$ are determined by the properties of the ID reader, while these parameters cannot be determined on acquisition of the ID.
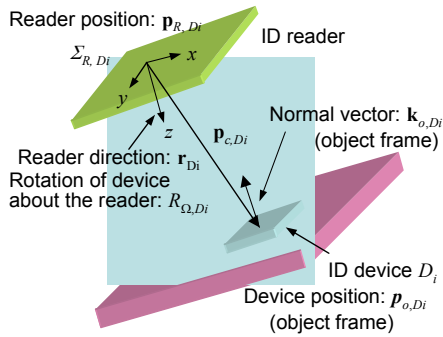

Figure 2: Model of ID reader and ID device

The geometrical relation between the ID reader and the ID device D_i on acquisition of the ID is described as follows:

$$\mathbf{p}_{R,D_i} + {}^{W}R_{R,D_i}\mathbf{p}_{c,D_i} - {}^{W}R_o\mathbf{p}_{o,D_i} - \mathbf{p}_o = \mathbf{0} \qquad (1)$$

$$^{W}R_{R,D_i}\begin{vmatrix} 0 \\ 0 \\ 1 \end{vmatrix} \cdot {}^{W}R_o R_{\Omega_{D_i}}\mathbf{k}_{o,D_i} = -1 \qquad (2)$$

$$^{W}R_{R,D_i}\begin{vmatrix} 0 \\ 0 \\ 1 \end{vmatrix} \times {}^{W}R_o R_{\Omega_{D_i}}\mathbf{k}_{o,D_i} = \mathbf{0} \qquad (3)$$

where ${}^{W}R_o$ and $\mathbf{p}_o$ indicate the object orientation and position, respectively. ${}^{W}R_o$ is given by a rotation matrix. The set of the object pose is described by the parameter sets of the ID reader. For each ID acquisition, the geometrical relation between the reader and the device is defined. The product set of the object poses is the estimated object pose.

3.2 Object pose estimation using multiple ID devices

We describe a model of estimation of the object pose using minimum two ID devices attached to the object based on the relative displacement between each ID device. It is difficult to estimate the relative position and orientation in the communication area of the reader when the reader acquires the ID of the device. In addition, the orientation of the device

attached to the object is not determined by the definition of the reader model.

The proposed method estimates the object pose as the model estimation based on the measurement data of the ID reader and the devices. We add the assumption that the position of the device with respect to the reference coordination frame is the position of the reader, and the device direction faces the front of the ID reader. Therefore, we consider $\mathbf{p}_{c,Di}$ in equation (1) and ${}^{R}W_{Di}$ in equations (2)(3) as the minimal displacement from the reader and initial rotation matrix, respectively.

We define the model of the pose estimation based on the measurement of the pose of the ID reader with former assumption. Equations (1)(2)(3) are derived as follows:

$$^{W}R_o\mathbf{p}_{o,D_i} + \mathbf{p}_o = \mathbf{p}_{R,D_1} \qquad (4)$$

$$\mathbf{r}_{D_i} \cdot {}^{W}R_o\mathbf{k}_{o,D_i} = -1 \qquad (5)$$

$$\mathbf{r}_{D_i} \times {}^{W}R_o\mathbf{k}_{o,D_i} = \mathbf{0} \qquad (6)$$

where $\mathbf{r}_{Di}$ indicates the direction vector of the ID reader when the reader acquires the ID of the device. The size of direction vector $\mathbf{r}_{Di}$ is 1. The estimation parameters are object pose $\mathbf{p}_o$ and ${}^{W}R_o$, we set the matrix of the object orientation ${}^{W}R_o$ as

$$^{W}R_o = \begin{bmatrix} \mathbf{n}_o & \mathbf{s}_o & \mathbf{a}_o \end{bmatrix} = \begin{bmatrix} n_{o,x} & s_{o,x} & a_{o,x} \\ n_{o,y} & s_{o,y} & a_{o,y} \\ n_{o,z} & s_{o,z} & a_{o,z} \end{bmatrix}.$$

We obtain seven equations by each ID acquisition based on equations (1)(2)(3) for vector $\mathbf{x}^{T} = [\mathbf{p}_o^{T}\ \mathbf{n}_o^{T}\ \mathbf{s}_o^{T}\ \mathbf{a}_o^{T}]^{T}$. We can estimate the object pose using multiple devices since the object pose with respect to the reference coordination frame is not changed. From equations (4)(5)(6), if there are the ID devices that the object direction is the same and opposite as that of the other device, efficient equations for pose estimation is decreased. We express the vector $\mathbf{a}_o$ by the cross product of vector $\mathbf{n}_o$ and $\mathbf{s}_o$ since the matrix ${}^{W}R_O$ is the orientation matrix.

Through the above process, the object pose is estimated using the measurement data of the ID reader when the reader acquires the ID of the device. In the case that the reader acquires the ID of the device that the device direction is the same and opposite as that of the other device, efficient equations for pose estimation is decreased, however, the equation (1) can be set independently since the position of the other device is different. As a result, at least 10 equations are defined for nine parameters of the object. Therefore, the method can estimate the object pose based on the acquisition of the ID of at least two devices as shown in Figure 3.
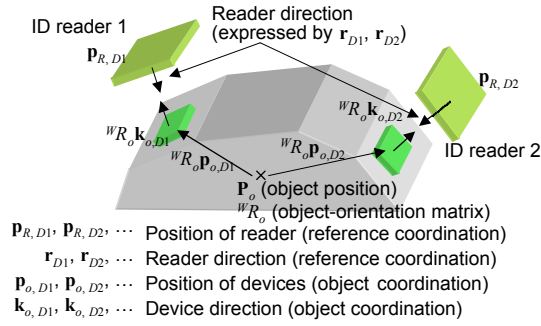
Figure 3: Object pose estimation using two ID devices.

3.3 Features of proposed method

We describe the features of the proposed pose estimation method using multiple ID devices. The method can estimate the object pose based on acquisition of the ID of at least two ID devices. In addition, the method can estimate the object pose using the acquisition of the device attached to the same side of the object. This fact makes the motion planning of the ID reader easier. In the previous pose estimation method, the device poses of the devices that are attached to the other side of the object are needed.

The method uses the direction of the ID reader with respect to the reference coordination frame. This fact is that the motion planning of the ID reader is considered. If the direction of the ID reader is not considered, the geometrical relation between the reader and the device is not obtained when the ID reader acquires the ID of the first device. The other sensing device is needed to obtain the geometrical relation between the reader and the device. By the proposed method, the object side that the ID device is attached faces the front of the ID reader. The workers or robots can move the ID reader using acquisition of the ID of the other device.

The method uses the direction of the ID devices with respect to the object coordination frame. This fact enables the motion planning of the ID reader. Moreover, the direction of the ID device is easy to register the database, since the device is attached to the object. In fact, the direction of the device can be registered as the normal vector of the object surface; the parameters are need for production of the construction materials.

The object pose estimated by the proposed method is not always satisfied that the relative position of each device $\mathbf{p}_{c,Di}$ and $^{R}W_{Di}$ from the estimated object pose can be out of the range of the ID reader. However, the ID reader acquires the ID of the device at the measured object pose. We can derive the real set of the object pose using the estimated object pose as the initial value.

4. OBJECT POSE ESTIMATION EXPERIMENT

This section describes an object-pose estimation experiment to show feasibility of the proposed method. The experiment assumes that workers obtain the ID of the device attached to the object using the small RFID reader. First, we introduce the numerical simulation including the pose error of the reader. Next, we show the pose estimation experiment using the motion-capture system.

4.1 Numerical examples

We have carried out the numerical simulation of the pose estimation including the pose error of the ID reader to show feasibility of the method. The ID reader has communication area and the reader can acquire the ID of the device that is inclined from the ID reader. The fact causes the error and variance of the pose estimation results. We have carried out the simulation on the assumption that the workers and robots acquire the ID of the device that is inclined in the communication area of the reader.

We set two conditions of the layout of the ID devices; aligned two ID devices that are same direction (condition 1), and not-aligned three ID devices that are same direction (condition 2), respectively. The registered positions of the ID devices with respect to the object coordination frame are set at random. The distance between each ID device is set 1.0 – 2.0 [m]. In condition 2, the direction of the devices is set as the normal vector of the plane whose vertices indicate the device position. That is, the condition 2 is considered as the condition that the ID devices are attached to the same side of the object. The object is set in the reference coordination frame at random.

The pose of the ID reader is set the position of the ID device with respect to the reference coordination frame for position and the opposite direction of the device with respect to the reference coordination frame, respectively. In addition, the translational and rotational displacements of the reader are set at random. The ranges of the displacements are 20 [mm] for each axis about the translational displacement and 5, 30 [deg] for each axis about the rotational displacement, respectively. The distribution of the displacement is uniform distribution.

We have carried out the pose estimation under the following conditions. We used the object pose based on Gauss – Newton Method. The initial value of the object pose was set $\mathbf{p}_o = [0, 0, 0]^{T}$ and the first and second column of the initial orientation matrix as $\mathbf{n}_o$ and $\mathbf{s}_o$, respectively. We set 10 poses of the object, and estimate the object pose 10 times for each object layout.

Table 1 shows the average estimation error of the object pose for each condition of the acquisition. This table shows the average error of the position and the average error of the angle for each axis under the accurate and worst accurate case. Table 2 shows the pose error of the worst accurate case with respect to the position accuracy. These tables show the result of the numerical simulation; the simulation results are qualitative result, however, the results are not analytical.

Table 1: Average estimation error of object pose in numerical simulation.

Conditions	Average Position Error (Min. – Max.) [mm]	Average error of angle for each axis (Min. – Max.) [deg]
Condition 1 (Orientation err.: 5 [deg])	32.70 – 74.06	0.30 – 2.73
Condition 2 (Orientation err.: 5 [deg])	29.90 – 64.76	0.13 – 2.46
Condition 1 (Orientation err.; 30 [deg])	62.00 – 406.75	3.49 – 19.59
Condition 2 (Orientation err.: 30 [deg])	27.55 – 64.86	0.13 – 2.04

As shown in Tables 1 and 2, in condition 1, the error of the object pose increases as the orientation error of the ID reader. On the other hand, in condition 2, the error of the object pose does not increase as the orientation error of the ID reader. In the case that the ID reader acquires the ID of the collinear and same-directed devices, the estimated pose error of the object increases as the orientation error of the ID reader increases.

Table 2: Position error in the worst accurate case.

Conditions	Largest position error [mm]	Orientation error for each axis [deg] (Roll – Pitch – Yaw)
Condition 1 (Orientation err.: 5 [deg])	153.47	2.66 – 1.84 – 6.60
Condition 2 (Orientation err.: 5 [deg])	115.18	1.11 – 0.31 – 5.70
Condition 1 (Orientation err.; 30 [deg])	937.28	9.56 – 2.00 – 34.20
Condition 2 (Orientation err.: 30 [deg])	112.93	1.00 – 1.17 – 1.49

If the workers or robots estimates the object pose based on the acquisition of the ID of the collinear devices, it is difficult to estimate object pose accurately and stably because of the range of the communication area of the reader and the range of the inclination of the device to the front of the ID reader. The ID reader has the range of the inclination of the device to the front of the ID reader.

The workers or robots can estimate the object pose using the additional ID devices to improve the pose accuracy. They can obtain the position and direction of the neighbor ID device when they acquire the ID of the device attached to the object, since they can search for the information of the other device attached to the object. In addition, the workers or robots make a motion plan for acquisition of the other ID of the device if the workers or robots estimate the device pose precisely using the range of the communication area of the ID reader [9].

4.2 Pose estimation experiment

Next, we have carried out the pose estimation experiment using the motion capture system to show feasibility of the proposed method. The experiment has been carried out on the assumption that the workers at the construction site read the ID devices attached to the object using the small ID reader such as the mobile ID reader.

Figure 4 shows the procedure of the pose estimation experiment using the motion capture system. The motion capture system obtains position and direction of the ID reader, then the experimental system estimates the object pose using the data, which are position and direction of the ID devices. On the other hand, the motion capture system obtains the position of the markers attached to the object, then the experimental system estimates the object pose using the motion capture data. The estimated object pose is compared with the object pose estimated by the acquisition of the ID from the devices attached to the object. In this experiment, the operator moves the ID reader by hand.
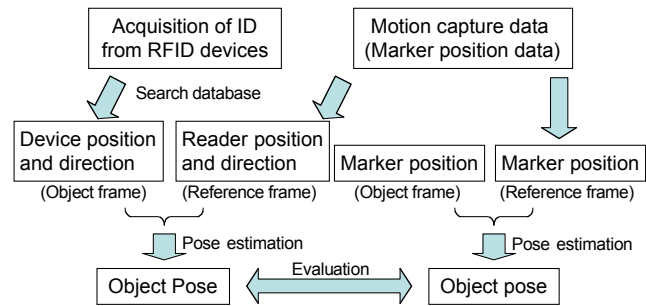
Figure 4: Procedure of pose estimation experiment.

Table 3: Estimation error in pose estimation experiment.

Conditions	Average pose error Upper: (x – y – z) [mm] Lower: (R – P – Y) [deg]	Std. dev. of object pose Upper: (x – y – z) [mm] Lower: (R – P – Y) [deg]
Level object (3 devices)	9.83 – 11.00 – 19.39 0.38 – 1.83 – 12.60	2.46 – 1.89 – 2.30 0.14 – 0.41 – 0.19
Level object (2 devices)	16.12 – 4.38 – 20.67 1.43 – 2.35 – 11.62	5.48 – 4.31 – 5.07 0.42 – 0.46 – 0.63
Inclined object (3 devices)	14.25 – 5.72 – 16.56 2.50 – 0.11 – 6.82	4.02 – 1.55 – 2.29 0.83 – 0.53 – 0.52
Inclined object (2 devices)	11.30 – 26.87 – 29.71 5.11 – 1.69 – 2.77	8.31 – 6.32 – 5.24 1.24 – 1.22 – 0.84

The registered positions of the ID devices with respect to the object coordination frame are set D_1 to D_3 as (207, 0, -290), (-193, 0, -235) and (165, 0, 320) [mm], respectively. The direction of each device $\mathbf{k}_{o,Di}$ is set (0, 1, 0). We set the object in the field of measurement of the motion capture system with propriety and estimate the object pose.

We have carried out the pose estimation under the following conditions. We used the object pose based on Gauss – Newton Method. The initial value of the object pose was set $\mathbf{p}_o = [0, 0, 0]^T$ and the first and second column of the initial orientation matrix as $\mathbf{n}_o$ and $\mathbf{s}_o$, respectively. We set nine poses of the object, and estimated the object pose using ID reader motion. The operator acquires the IDs of the devices attached to the object in the predetermined sequence, $D_1 \rightarrow D_2 \rightarrow D_3$ in each object layout. We compared the estimation results using three ID devices with those using two ID devices. The estimation results

correspond with the result based on the aligned two ID devices and not-aligned three ID devices, respectively.

We have estimated the pose of the object under various conditions, then the error and standard deviation of the object pose using the not-aligned three ID devices are small. Table 3 shows the estimation error and standard deviation of the object pose when the operator estimates the same object pose 10 times. The upper row of the element in the table indicates the position error or standard deviations for each axis. The lower row of the element indicates the orientation error or standard deviations for each axis, which is Roll – Pitch – Yaw. From table 2, the workers or robots can estimate the object pose in each condition. In addition, they can estimate the object pose accurately and stably using not-aligned ID devices. The estimation results are qualitative; the quantitative analysis of the pose error in the estimation is required in order to introduce the proposed method in the real environment for construction automation.

5. CONCLUSIONS

This paper describes a method of estimation of object pose using multiple ID devices for construction automation. We have introduced the geometrical model of the ID reader and the device in acquisition of the IDs. The proposed method can estimate the object pose using at least two ID devices attached to the object. In the paper, we discuss the properties of the method based on the geometrical model of the ID reader. Experimental results have shown feasibility of the proposed method.

The proposed method uses the position and direction of the ID reader and the devices attached to the object. Using the direction of the ID device makes the registration of the object pose easier. In addition, the assumption of the ID reader has feasibility of the development of the ID reader that the workers operate at the construction site. This features are more suitable for the real environment.

The quantitative analysis of the pose error in the estimation, improvement of the pose accuracy using the other sensing devices, simplification of the pose estimation, and the planning of the ID reader and the robots at the construction site are the future works for realization of the proposed method.

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