Advances in Robotics Research, *Vol. 2, No. 1 (2018) 45-57*
DOI: https://doi.org/10.12989/arr.2018.2.1.045

Projection mapping onto multiple objects using a projector robot

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(Received January 1, 2018, Revised February 22, 2018, Accepted February 23, 2018)

Abstract. Even though the popularity of projection mapping continues to increase and it is being implemented in more and more settings, most current projection mapping systems are limited to special purposes, such as outdoor events, live theater and musical performances. This lack of versatility arises from the large number of projectors needed and their proper calibration. Furthermore, we cannot change the positions and poses of projectors, or their projection targets, after the projectors have been calibrated. To overcome these problems, we propose a projection mapping method using a projector robot that can perform projection mapping in more general or ubiquitous situations, such as shopping malls. We can estimate a projector's position and pose with the robot's self-localization sensors, but the accuracy of this approach remains inadequate for projection mapping. Consequently, the proposed method solves this problem by combining self-localization by robot sensors with position and pose estimation of projection targets based on a 3D model. We first obtain the projection target's 3D model and then use it to accurately estimate the target's position and pose and thus achieve accurate projection mapping with a projector robot. In addition, our proposed method performs accurate projection mapping even after a projection target has been moved, which often occur in shopping malls. In this paper, we employ Ubiquitous Display (UD), which we are researching as a projector robot, to experimentally evaluate the effectiveness of the proposed method.

Keywords: projection mapping; projector robot; multiple objects; self-localization; point cloud

1. Introduction

The popularity of projection mapping continues to increase, and it is being used in various situations (Rok *et al.* 2013, Lee *et al.* 2015). Projection mapping is generally conducted at large-scale events, for example, onto stations or castles. Another example is projection mapping in theaters or at live musical performances. Projection mapping is also used in advertisements. With projection mapping, we can show items more attractively and advertise products with one mannequin by projecting images of various clothing onto it. Although projection mapping is done

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http://www.techno-press.org/?journal=arr&subpage=7 ISSN: 2287-4976 (Print), 2287-4984 (Online)

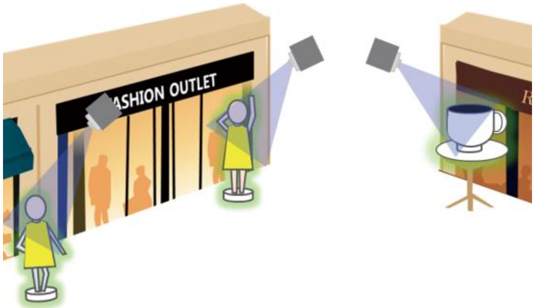

Fig. 1 Assumed situation and conventional setup

Fig. 2 Proposed method

in many different circumstances, most are conducted during special events.

In contrast, we conduct projection mapping in more general situations, as shown in Fig. 1. We achieve projection mapping onto multiple objects that are placed in shopping malls or train stations, for example. In such situations, several problems occur based on conventional projection mapping methods.

Conventional projection mapping requires a calibration process that estimates in advance the relative relationship between a projector and its target. After calibration, we cannot move the projector or the projection target, since moving them would require recalibration. When projecting onto multiple objects, a dedicated projector is required for each projection target. Accordingly, many projectors are required for a given deployment. Since we need to calibrate all of the projectors, performing these projector calibrations is time-consuming. Thus, using the conventional projection mapping methods, projection mapping would be difficult in the situation illustrated in Fig. 1.

We aim to solve these conventional projection mapping problems and to achieve projection mapping onto multiple objects by introducing a robot equipped with a projector: a *projector robot* (Kasetani *et al.* 2015). As shown in Fig. 2, the projector robot first moves to its first designated position and performs the projection mapping. After that, it moves to its next designated position and carries out the next stage of projection mapping. Using our method, we can achieve projection mapping onto multiple objects even when these objects are moved.

Recently, some developers have used robot arms to perform projection mapping from moving projectors or onto moving targets, such as "Box" (Box 2013). However, because these systems require preparation in advance to establish the correspondence between the robot arm's movements and the projection contents, the projectors or projection targets cannot be moved freely, thus limiting the applicable situations for their use. Some researchers have proposed projection mapping onto deformable objects (Narita *et al.* 2017, Bermano *et al.* 2017, Siegle *et al.* 2017), but these works have not focused on projection mapping onto multiple objects or the required movement compensation for target objects that have moved.

Several projector robots have been proposed and developed (Cerevo Inc. 2016, Keecker 2017, Machino *et al.* 2006, Lee 2007, Park and Kim 2009, Choi *et al.* 2013, Maegawa *et al.* 2013, Sticker *et al.* 2015, Tatsumoto *et al.* 2017) that are equipped with self-localization sensors (odometry, laser range finder, etc.) and a projector. By using these sensors, we can obtain the robot's position and pose. As a result, the projector's position and pose in the environment can also be obtained. However, the position and pose estimation accuracy are insufficient for projection mapping.

In this paper, we propose a method to achieve projection mapping onto multiple objects with a projector robot by combining self-localization by the robot's sensors with position and pose estimation of projection targets based on a 3D model. An RGB-D camera, such as KINECT, is mounted on the projector robot to obtain the 3D point cloud of the projection target. With the obtained 3D point cloud, we estimate the projection target's accurate position and pose for accurate projection mapping.

Projection mapping is also called Spatial Augmented Reality (SAR) (Bimber and Rasker 2005) or Projection-based Augmented Reality, and many researchers have proposed projection mapping systems in the context of AR (Schöning *et al.* 2009, Mine *et al.* 2012, Leutert *et al.* 2013, Akiyama *et al.* 2016, Fukiage *et al.* 2017). However, such research mainly focused on projections onto planar surfaces and did not consider projections onto 3D objects. In addition, since they did not employ a projector mounted on a robot, its projection areas are limited.

On the other hand, these research efforts could achieve various effects by projecting additional information such as changing the colors/appearances of the original surfaces (Akiyama *et al.* 2016), or animating static objects (Fukiage *et al.* 2017). In addition, aiming to introduce robots in public spaces such as shopping malls or museum, recently, many researchers have proposed service robots and their behavior models (Glas *et al.* 2012, Noguchi *et al.* 2015, Doering *et al.* 2015). By combining these research works and our proposed method, we will be able to achieve more attractive projection mapping.

Section 2 describes an overview of our proposed method. Section 3 describes the proposed projection mapping onto multiple objects. Section 4 shows the experimental results of our proposed method, and Section 5 summarizes our paper.

2. Overview of proposed method

2.1 Requirements of projector robot

We first describe the following requirements of the projector robot for our proposed method:

- The robot must be able to conduct such self-localization as Simultaneous Localization and Mapping (SLAM) (Brenneke *et al.* 2003, Cole and Newman 2006) and move to designated positions.
- It must be able to capture a 3D point cloud of its surrounding environment with an RGB-D

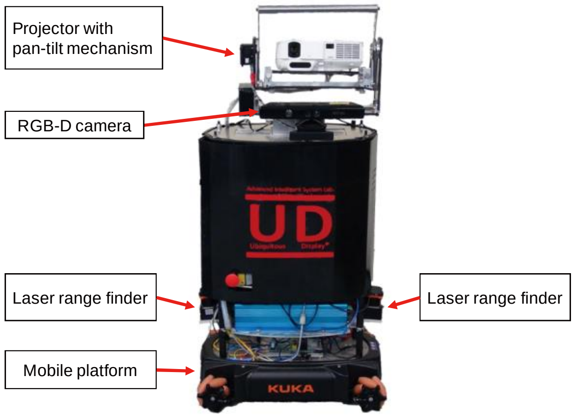

Fig. 3 Ubiquitous display

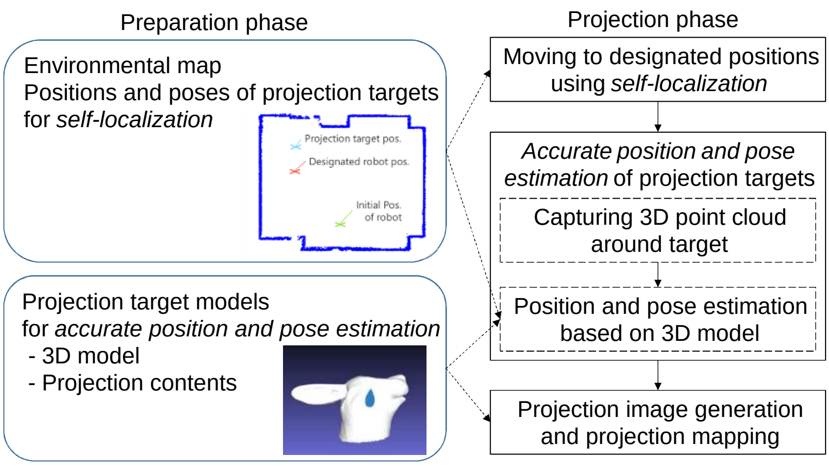

Fig. 4 Process flow

camera for accurate position and pose estimation of projection targets from the projector.

As an example of a projector robot that satisfies these requirements, we introduce our research on Ubiquitous Display (UD) (Lee 2007, Maegawa *et al*. 2013), which is a robot with a projector that can provide human-centered information provisions (Lee 2007). Fig. 3 shows UD's system configuration, which consists of a mobile platform (KUKA youBot), a projector with a pan-tilt mechanism, and such sensors as two laser range finders (LRF) (Hokuyo UTM-30LX), an odometry (included in KUKA youBot), and an RGB-D camera (Microsoft Kinect V1) (Fig. 3). UD satisfies the above requirements. In this paper's experiment, we employ it as a projector robot.

2.2 Process flow

Fig. 4 shows our proposed method's process flow, which is divided into two phases: preparation and projection. Each phase mainly consists of processes for self-localization and accurate pose estimation of the projection targets.

In the preparation phase, we obtain data required for projection mapping by the projector robot. The proposed method assumes that a 3D model of the projection target and the projection contents and an environmental map and the position and pose of the projection target are given in advance (Fig. 4 left). First, we measured the 3D model of the projection target and manually set its position and pose. The projection contents are prepared on the constructed 3D model.

In the projection phase, the robot first moves to its designated position for the projection based on the environmental map. Next, it captures the 3D point cloud around the projection target. Aligning the constructed 3D model of the projection target with the captured 3D point cloud, we estimate the accurate 3D position and the target's pose in the environment. Finally, we generate projection images for projection mapping based on the target's estimated position and pose for accurate projection mapping.

3. Projection mapping by projector robot

3.1 Definition of coordinate system

Before describing the method's details, we first define the coordinate systems used in this paper (Fig. 5).

A world coordinate system $\boldsymbol{C}_w$ is a manually defined coordinate scheme. Environmental maps are expressed by this coordinate. The projector and RGB-D camera coordinate systems $\boldsymbol{C}_p, \boldsymbol{C}_c$ are the coordinate systems of the projector and the RGB-D camera, respectively. The relative relation between them, $\boldsymbol{R}_{cp}, \boldsymbol{T}_{cp}$, are calibrated in advance.

The model coordinate system $\boldsymbol{C}_m$ is defined as a coordinate whose origin is the model's centroid, and the Y and Z axes are defined manually as the model's upward and front directions.

3.2 Preparation phase

In the preparation phase, we obtain a 3D model of the projection targets, the projection contents, and the environmental map.

3.2.1 Preparation of projection target models

First, we built a 3D model of the projection targets by employing KinectFusion (Newcombe *et al.* 2011). We converted the obtained 3D model to the model coordinate and used it for estimating the position and pose of the projection targets.

After building the 3D model, we made contents of the projection mapping by coloring it. In the current implementation, we employed Meshlab (Cignoni *et al.* 2008). Figs. 6 and 7 show an example of the projection target and its colored 3D model for projection mapping.

3.2.2 Construction of environmental map

Next we construct an environmental map so the robot can move to its designated positions with Simultaneous Localization and Mapping (SLAM) (Brenneke *et al.* 2003, Cole and Newman 2006). Although the constructed environmental map varies depending on the robot's sensors, an example is shown in Fig. 8 of an environmental map constructed by the UD. In the current implementation, we employed the ICP-SLAM algorithm from the Mobile Robot Programming Toolkit (MRPT) (MRPT n.d.) to construct the environmental map.

Since the proposed method requires the positions and poses of the projection targets, these values are measured in advance. In addition, we defined the robot's positions when it performs projection mapping onto each projection target. These positions are also required in the proposed method. Here, note that unlike conventional projection mapping, our proposed method does not need accurate positions or poses of the projection targets and the projector. This is an advantage of our proposed method.

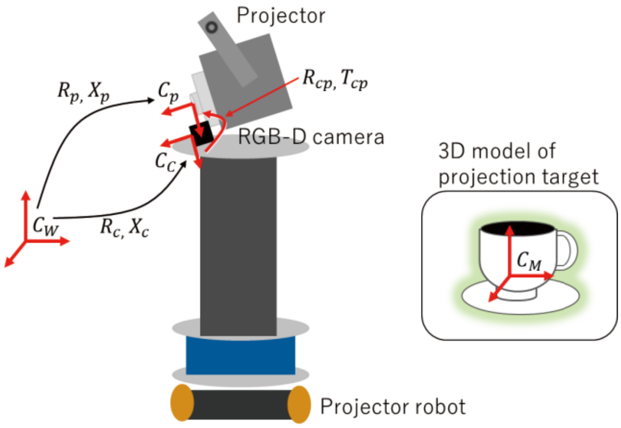

Fig. 5 Coordinate systems

Fig. 6 Example of projection target

Fig. 7 Example of 3D model and projection content

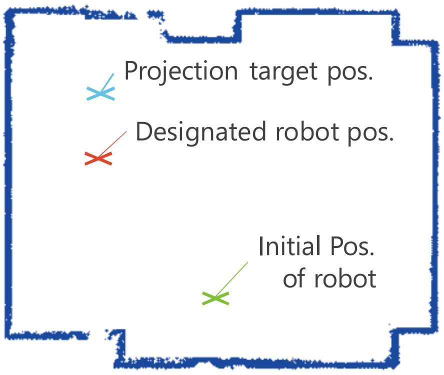

Fig. 8 Example of environmental map

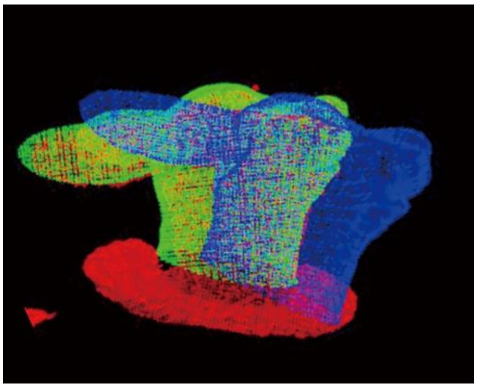

Fig. 9 Example of ICP results (blue: initial, green: ground truth, red aligned results)

Fig. 10 Example of projection before estimation

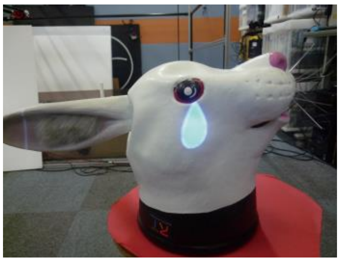

Fig. 11 Example of projection after estimation

3.3 Projection phase

3.3.1 Moving to the designated positions

As the first step of the projection phase, the projector robot moves to its designated position based on its self-localization. After that, it changes the poses of the projector and the RGB-D camera to face to the projection target, based on the robot's current position and the given projection target position. For self-localization in the current implementation, we again employed ICP-SLAM from the MRPT (MRPT n.d.).

3.3.2 Accurate position and pose estimation of projection targets

Subsequently, to estimate the relative relationship between the projector and the projection target, the robot captures the 3D point cloud data of the scene around the projection target, and we align the projection target's 3D model to the obtained point cloud data.

We employed the Iterative Closest Point (ICP) algorithm for the alignment. Here, since it requires initial values, we calculate them for the alignment. Let $\boldsymbol{R}_{ti}^{(c)}, \boldsymbol{X}_{ti}^{(c)}$ be the initial values of the pose and position of the projection target in the RGB-D camera coordinate $\boldsymbol{C}_c$, $\boldsymbol{R}_{ti}^{(c)}, \boldsymbol{X}_{ti}^{(c)}$ can be calculated as follows

$$\begin{aligned} \boldsymbol{R}_{ti}^{(c)} &= \boldsymbol{R}_{wc}\boldsymbol{R}_t \\ \boldsymbol{X}_{ti}^{(c)} &= \boldsymbol{R}_{wc}(\boldsymbol{X}_t - \boldsymbol{X}_c), \end{aligned} \tag{1}$$

where $\boldsymbol{R}_t, \boldsymbol{X}_t$ are the projection target's pose and position given in the environmental map, $\boldsymbol{R}_{wc}$ is the rotation matrix from $\boldsymbol{C}_w$ to $\boldsymbol{C}_c$, and $\boldsymbol{X}_c$ is the projector position in $\boldsymbol{C}_w$. Note that the captured 3D point cloud is in RGB-D camera coordinate $\boldsymbol{C}_c$. Using $\boldsymbol{R}_{ti}^{(c)}, \boldsymbol{X}_{ti}^{(c)}$ as the initial values for ICP, we can estimate $\boldsymbol{R}_t^{(c)}, \boldsymbol{X}_t^{(c)}$, which are the projection target's accurate position and pose in $\boldsymbol{C}_c$. Currently, we employ an implementation of the ICP algorithm from the Point Cloud Library (PCL) (Rusu and Cousins 2011). Fig. 9 shows an example of the ICP results, where the blue mark is the initial position and pose, the green mark is the ground truth, and the red mark indicates the aligned results.

To generate projection images, we require $\boldsymbol{R}_t^{(p)}, \boldsymbol{X}_t^{(p)}$, which are the projection target's position and pose in projector coordinate $\boldsymbol{C}_p$. $\boldsymbol{R}_t^{(p)}, \boldsymbol{X}_t^{(p)}$ can be calculated as

$$\begin{aligned} \boldsymbol{R}_{t}^{(p)} &= \boldsymbol{R}_{cp}\boldsymbol{R}_t^{(c)} \\ \boldsymbol{X}_{t}^{(p)} &= \boldsymbol{R}_{cp}\boldsymbol{X}_t^{(c)} + \boldsymbol{T}_{cp}, \end{aligned} \tag{2}$$

where $\boldsymbol{R}_{cp}, \boldsymbol{T}_{cp}$ are the relative relations from $\boldsymbol{C}_c$ to $\boldsymbol{C}_p$.

3.3.3 Generation of projection images

Finally, we generated images for projection mapping by projecting the colored 3D model to the 2D projector coordinate. Let $\boldsymbol{x}^{(p)}$ be the 2D positions in the 2D projector coordinate and calculate it as follows

$$\boldsymbol{x}^{(p)} = \boldsymbol{A}_p\left(\boldsymbol{R}_t^{(p)}\boldsymbol{X}_t^{(m)} + \boldsymbol{X}_t^{(p)}\right), \tag{3}$$

where $\boldsymbol{A}_p$ is the intrinsic matrix of the projector and $\boldsymbol{X}_t^{(m)}$ is the 3D model data in model coordinate $\boldsymbol{C}_m$.

Thus, the projection images aligned to the projection target can be accurately generated to achieve projection mapping onto multiple objects by the projector robot. Figs. 10 and 11 show examples of the projection before and after position and pose estimation of the projection targets using ICP.

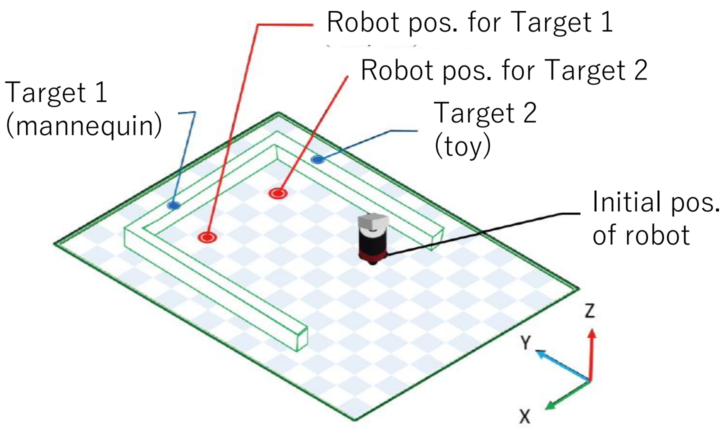

Fig. 12 Experimental environment

Fig. 13 Projection target 1(mannequin)

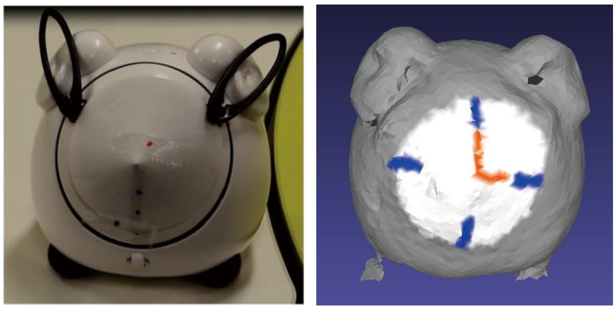

Fig. 14 Projection target 2 (toy)

Fig. 15 Projection result of target 1

Fig. 16 Projection result of target 2

Table 1 Projection mapping errors [mm]

	Target 1	Target 2
1st	4.0	6.0
2nd	6.0	6.0
3rd	12.0	19.0

4. Experiment

To show the effectiveness of the method, we performed the following experiment. As shown in Fig. 12, two projection targets were placed in the environment. We performed projection mapping on them with the projector robot. As described above, we employed the UD shown in Fig. 3 as the projector robot. Figs. 13 and 14 show the projection targets and their projection contents. In the experiment, we used only an odometry for self-localization.

The following are the projection mapping procedures. First, the robot moved to projection target 1 from its initial position and performed projection mapping on it. Next, the robot moved to projection target 2 and performed projection mapping on it. After that, the robot returned to target 1 and performed projection mapping on it. Finally, the projection mappings were performed three times for each target. Figs. 15 and 16 show examples of projection mapping.

To evaluate the accuracy of our proposed projection mapping, we measured projection errors as follows. The robot first performed projection mapping from the ideal position and pose. Here, the projection contents included markers for measuring projection errors, and we manually marked the positions to which they were projected. After that, the robot went back to its initial position and moved to the designated positions to perform the proposed method's projection mapping. Finally, we manually measured the marked positions to obtain the projection errors. Table 1 shows the results. The errors of the 1st and 2nd projections were less than 6 [mm]; however, the errors of the 3rd projections increased, perhaps because the self-localization errors accumulated. This increased the error of the initial value for ICP, and the errors of the position and pose estimation increased.

5. Conclusions

In this paper, we proposed projection mapping onto multiple objects with a projector robot. Although conventional projection mappings are limited to such special situations as live theater or outdoor events, our proposed method achieved projection mapping in more general situations, for example, projections onto various items in a shopping mall. Although we can estimate the projector's position and pose using the robot's self-localization sensors, the accuracy for projection mapping is inadequate. Therefore, our proposed method overcame this problem by combining self-localization by robot sensors with accurate position and pose estimation of the projection targets based on 3D models of the targets. We capture the projection target's 3D models in advance and accurately estimate the target's position and pose based on the captured 3D models. These processes enable us to achieve accurate projection mapping. In the experiment, we employed Ubiquitous Display (UD) as a projector robot and confirmed that accurate projection mapping can be performed.

Future works will improve the projection mapping accuracy. Recently, some researchers propose methods for projection mapping onto a moving object (Chen *et al.* 2015, Sueishi *et al.* 2017). Although these methods employ high speed cameras or projectors, by improving our method based on these techniques, we will be able to improve the projection mapping accuracy. We are also developing an environment for creating projection contents. Furthermore, since our proposed method is based on a projector robot, we will exploit that advantage and investigate robot services that might provide not only projection mapping but also navigation or other information.

Acknowledgements

This research was supported by JSPS KAKENHI Grant Number 17K00372.

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