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A Portable 6-DOF Motion Tracker Using High-Accuracy AR Markers – First Report on the Feasibility

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Abstract

We report a portable 6-DOF (six degrees of freedom) motion tracking system which uses high-accuracy AR markers. It enables easy measurement of 6-DOF motion of multiple tracking points by a single camera. We examined the measurement accuracy of the motion tracker by comparing with an ordinary motion-capture system. The pose estimation errors are about 5 [mm] in location (depth) and about 2 [deg] in orientation. We also demonstrated its availability and feasibility through a tracking test of human-arm motion.

1 Introduction

Human motion tracking technologies play important roles in many fields, e.g. sports science, medicine, rehabilitation, computer graphics, and amusements. There are a variety of approaches to motion tracking according to the physical principle. Zhou [1] classified them into eight categories and presented each merits and limitations. Table 1 shows the categories and their characteristics ("AR marker" at the last row is added by us). A great number of tracking system have been developed, but no single technology will work for all purposes [2]. Therefore, we have to select one or more technologies for optimal performance and trade-offs, in consideration of the application, the environment (e.g. small scale versus large scale, the potential for environment noise and occlusion) [4], and the cost.

Table 1. Comparison of different motion tracking system (modified version of Table 1 in [1])

Principle	Accuracy	Compactness	Cost	Drawbacks
Inertial	High	High	Low	Drifts
Magnetic	Medium	High	Low	Ferromagnetic materials
Ultrasound	Medium	Low	Low	Occlusion
Glove	High	High	Medium	Partial posture
Marker	High	Low	Medium	Occlusion
Marker-free	High	High	Low	Occlusion
Combinatorial	High	Low	High	Multi-disciplinary
Robot	High	Low	High	Limited motion
AR marker	**Medium**	**High**	**Very Low**	**Occlusion**

In our research project, we need to measure 6-DOF (six degrees of freedom) relative motions between an object and some parts of a human body, e.g. joints of arms, legs, or a neck. Although we do not need very high accuracy like a usual optical motion capture, we want to conduct the measurements anytime, anywhere, easily, quickly, and cheaply. Unfortunately, there was no existing tracking technology fulfilling our requirements. Therefore, we got to think of an "AR-marker-based motion tracker."

An AR marker is a small planar pattern providing its ID number and the relative 6-DOF pose to a camera (e.g. [5]). By using AR markers, we might be able to make up a motion tracker which enables an easy measurement of 6-DOF motion of multiple tracking points by a single camera. It will be a portable and low-cost system, and be beneficial to a person with the same needs as we have. However, such a motion tracker has not been realized because conventional AR markers are not so accurate in pose estimation. Instead, we adopted a high-accuracy AR marker "LentiMark" [6]. We developed a prototype of an AR-marker-based motion tracker using LentiMarks.

This paper is the first report on the proposed motion tracker. The organization of the paper is as follows: Section 2 - Overview of high-accuracy AR marker, Section 3 - Description of the AR-marker-based motion tracker we developed. Section 4 - Evaluation of the accuracy of the tracker, Section 5 - Measurement test in a realistic application, and Section 6 - Concluding remarks (issues in the future).

2 High-accuracy AR Marker

LentiMark is a high-accuracy AR marker using lenticular lenses. It was developed by us to solve one of the biggest problems of conventional AR markers, i.e. degradation of orientation accuracy in frontal observation. Fig. 1 shows a LentiMark. It consists of an existing AR marker (ARToolKitPlus [5]) for ID recognition, four dots, and two or four moiré patterns of which a black part seems to move according to the visual-line angle (Fig. 1 (right)). The moiré pattern is called VMP (Variable Moiré Pattern). The VMP consists of a lenticular lens and a stripe pattern (Fig. 1 (center)). The small difference of the pitch between

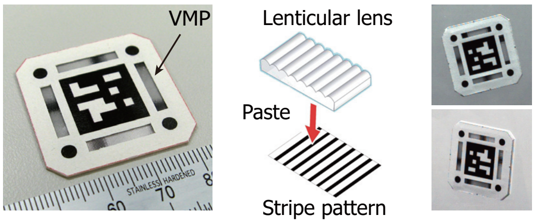

Figure 1. LentiMark: (left) LentiMark, (center) Structure of VMP, (right) Pattern variation according to visual-line angle.

lenses and stripes make the moiré and the movement of the pattern according to the visual-line angle.

The pose estimation is performed in three stages. First stage is the detection of the conventional AR marker located at the center of a LentiMark. Then, we estimate the marker pose by a conventional method, i.e. a geometrical calculation based on a homography and the positions of four dots detected. In the final stage, we modify the orientation by using the angle information calculated by the position of the black part in each VMP. LentiMark realized accurate and stable orientation estimation even by observation from frontal direction. The estimation error is less than 1 [deg] [6].

3 AR-marker-based 6-DOF Motion Tracker

3.1 System configuration

Figure 2 shows the conceptual diagram of the AR-marker-based 6-DOF motion tracker. The system consists of a computer, a camera, and multiple AR markers (LentiMarks). We attach each one marker having unique ID to each measuring point. The camera takes sequential images of all the markers in one field-of-view. We can use any type of camera from a small camera embedded in a laptop-computer to a high-speed camera. The images are processed by a computer. The relative 6-DOF pose of each marker and the camera is estimated by the processing program. This processing can be either online (quasi-real-time processing) or offline (batch processing).

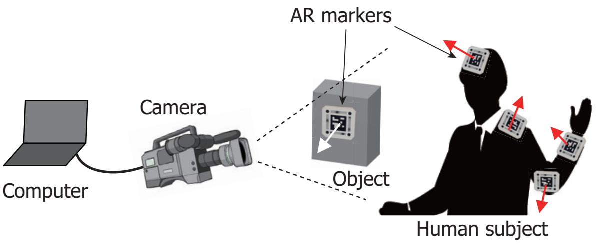

Figure 2. Conceptual diagram of AR-marker-based motion tracker.

3.2 Features of the system

3.2.1 Advantages

1. **Portability**: Needed sensor is only one camera. It does not have to be fixed to somewhere. The markers are small, thin, and lightweight. Therefore, the system is portable and we can conduct measurements anywhere. It is impossible by an optical motion-capture system.

2. **Richness of data**: We can get the ID number and the 6-DOF pose from one marker (measuring point). The data from multiple markers are got at one time. So, we can easily calculate the 6-DOF positional relations among multiple measuring points. It is impossible by non-visual tracking like inertial-sensor-based tracking.

3. **Ease of use**: The markers need no electrical power and no wire. And, we need no calibration, except one time of camera calibration for parameter identification. The preparation, the use, and the maintenance of the system are very easy.

4. **Low cost**: We can use any camera being used currently. The cost of the markers (LentiMarks) is unknown since they are not commercialized yet. However, they are a kind of printed pieces made of plastic, so the cost should be low compared with some sort of electric devices.

3.2.2 Disadvantages

1. **Visibility constraints**: The markers always have to be seen and be detected within an image frame. Therefore, we must be careful about occlusions and the measurement range. This system might be not adequate to tracking of widespread and drastically changing motions.

2. **Measurement accuracy**: The accuracy is much higher than that of conventional AR markers, but is not so high as that of optical motion capture systems. The quantitative evaluation of the accuracy is shown in the next section.

4 Evaluation of Measurement Accuracy

4.1 Comparison with a motion capture

We evaluated the measurement accuracy of the proposed motion tracker. We compared the 6-DOF tracking data of our system with those of a motion capture system (Cortex, Motion Analysis Corp.) with 16 cameras. The latter data are used as the true values. Fig.

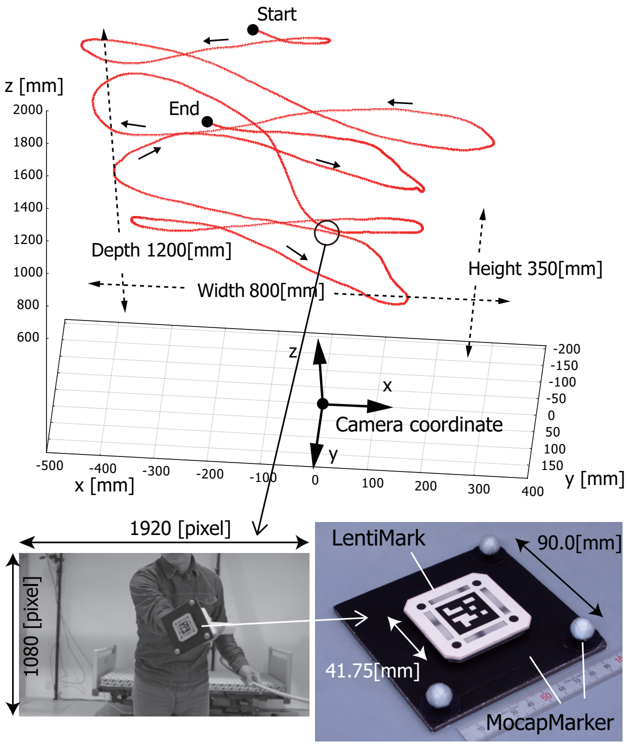

Figure 3. Evaluation of tracking accuracy: (top) Trajectory of test piece, (bottom left) One image from camera, (bottom right) Test piece.

3 (bottom right) shows the test piece. The size of the LentiMark is 41.75 [mm] on a side. Three reflective markers are attached around the LentiMark in order to measure the true values using the motion capture system. We call the marker composed of these reflective markers and a black board the MocapMarker (Fig. 3 (bottom right)). The center position and the axis directions are aligned between the MocapMarker and the LentiMark.

The test piece was moved along a trajectory shown in Fig. 3 (top) while its direction being changed, and the 6-DOF poses were tracked by a high-speed camera (Phantom Miro LC120, Vision Research) and the motion capture. The sizes of the envelope within which the test piece was moved are W 800 [mm]×H 350 [mm]×D 1200 [mm]. The resolution and the diagonal angle-of-view of the camera is 1920 [pixel]×1080 [pixel] and 49.3 [deg], respectively. The data rate is 200 [Hz]. The data processing was done offline.

The location errors and the orientation errors are shown in Table 2 and Table 3, respectively. Here, the orientation errors are evaluated using the angle displacement between each measured coordinate axis between the MocapMarker and the LentiMark.

Table 2. Location errors of LentiMark

Direction	x	y	z
Average error [mm]	-0.75	0.15	0.85
Standard deviation [mm]	0.90	0.47	3.62

Table 3. Orientation errors of LentiMark

Axis	x	y	z
Average error [deg]	1.23	0.97	1.21
Standard deviation [deg]	0.76	0.72	1.01

These results show that the proposed motion tracker achieves "modestly-high-accuracy" measurements despite that the we use AR markers and a single camera. We can say that the location error is about 5 [mm] and the orientation error is about 2 [deg].

4.2 Comparison with a conventional AR marker

LentiMark contains a conventional AR marker (ARToolKitPlus marker). We measured the 6-DOF poses of the marker at the same time as the LentiMark and the MocapMarker. Fig. 4 shows the measured location data in z-direction (depth-direction), for example. The error of LentiMark is much smaller than that of ARToolKitPlus. The size of the ARToolKitPlus marker is smaller than the LentiMark, so the accuracy could be worse a little than the LentiMark. However, this result exceeds that effect. In fact, the size of "far" LentiMark is smaller than the size of "near" ARToolKitPlus, in this experiment. This result shows that the proposed system will be feasible only when we use high-accuracy AR markers. The reason why LentiMark enables high-accuracy pose estimation is discussed in [7].

5 Motion Tracking Test

In order to validate the feasibility, we set a realistic analysis task, and conducted a measurement test.

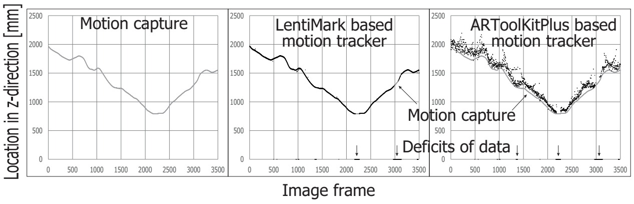

Figure 4. Comparison of location accuracy in z-direction.

5.1 Analysis task

The task we set is to analyze the difference of motion between dominant arm (the right arm in this case) and non-dominant arm. The target operation is an iteration of "throwing up a ball to the eye-level point and receiving the falling ball."

5.2 Equipment for measurement

Figure 5 shows the equipment for the test. We used three LentiMarks having each unique ID (#0, #1, and #2). We attached the markers to the subject's arm using rubber bands as shown in Fig. 5 (left). The camera is a small USB3.0 camera (Grasshopper3, Point Grey Research, Inc., Resolution is 1280 [pixel]×960 [pixel]) (Fig. 5 (center)). In addition, we used another LentiMark as the reference marker. It provides a base coordinate in the workspace. The necessity of the reference marker depends on the contents of the measurements.

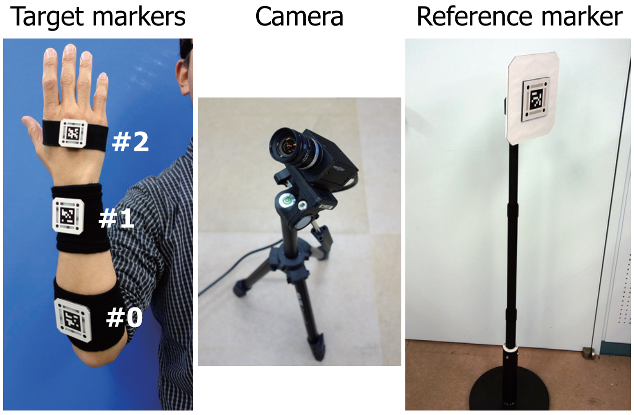

Figure 5. Equipment for measurement test

5.3 Measurement of reference marker

We measure the reference marker at the beginning of the analysis. The origin of the base coordinate is set at the bottom of the pole, and the 6-DOF pose of the reference marker is known. Therefore, we can get the 6-DOF pose of the camera in the base coordinate. This measurement is needed only one time if the position of the camera is fixed (Fig. 6 (top)).

5.4 Results of measurement and analysis

We measured the motions of both arms by our motion tracker (Fig. 6). The following sections show

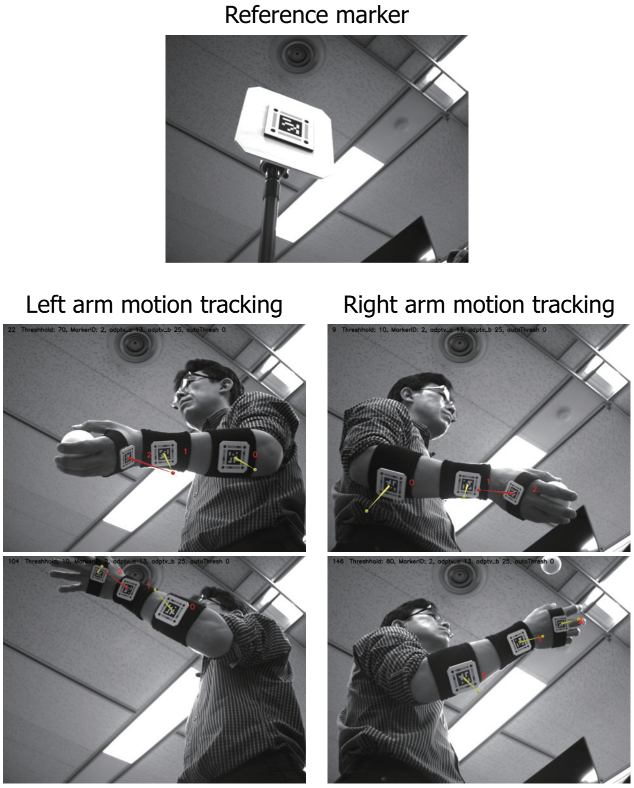

Figure 6. Scenes from measurement experiments

the results of analysis. They indicate that the motion tracker worked well and could collect meaningful data in a realistic application.

5.4.1 Bending motion of wrist

Figure 7 shows the bending angles of wrists of both arms. These data are acquired by calculating the relative pose of the marker #2 in the coordinate system of the marker #1. So, we need no reference marker in this case. We can see that the wrist motion of the dominant arm (right arm) is larger than that of the non-dominant arm. It means that the dominant arm utilizes the "snap" motion of the wrist more effectively.

5.4.2 Altitude of hand

Figure 8 shows the altitude of both hands. These data are acquired by calculating the relative pose of the marker #2 in the base coordinate system. We need the reference marker in this case. We can see that the peaks of the altitude of the non-dominant hand (left hand) are higher than those of the dominant hand. This indicates that the non-dominant arm uses motion of "whole arm" instead of the snap motion of the wrist in order to throw up the ball.

6 Concluding Remarks

We developed a prototype of a portable 6-DOF motion tracker using high-accuracy AR markers (LentiMarks). We validated its feasiblity through an evaluation of the measurement accuracy and a measurement test in a realistic application. Our conclusion of this first report is that the proposed motion tracker has many advantages which the other existing trackers do not have, and it is feasible if the requirements of the applications, e.g. acccuracy, range, complexity of motion, are fulfilled.

There are some issues found. One is the improvement of the accuracy and the robustness. The other is the speeding up of the marker measurement. Current algorithm of the marker recognition is naive. We plan to improve the algorithm introducing some filtering techniques for higher performance of the motion tracker.

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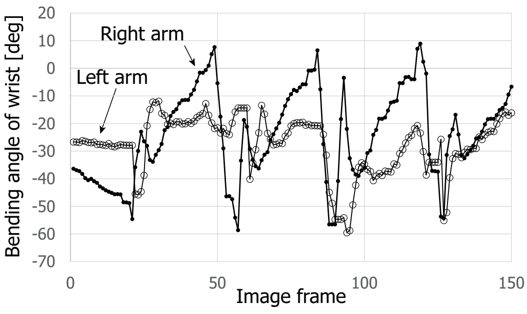

Figure 7. Bending angle of wrist.

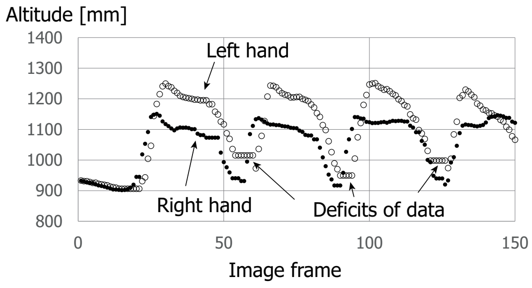

Figure 8. Altitude of marker #2