Abstract

In this paper, the development of a 3-dimensional odometry system for wheeled robots on loose soil in an application of planetary exploration is described. When a wheeled robot operates in a slippery environment, visual odometry, which is used to obtain flow-images of the ground with a CCD camera, is effective for the measurement of motion because it is a non-contact method. However, in the target condition, a measurement result with a conventional camera is not reliable with this method because the viewing area of the ground varies as a result of the changing distance between the camera and the ground as a result of the wheels sinking in loose soil. To solve this problem, we used a telecentric camera for visual odometry whose lens keeps the same field of view with a change of distance between the camera and the ground. Using the camera, we developed a 3-dimensional odometry system for our mobile robot to enable its positioning and navigation, and we validated the system with several experiments. In this paper, a structure and a performance test of the developed system is described. After that, the results of experiments in indoor (sandbox) and outdoor (seashore) environments are introduced.

keywords: mobile robot positioning, visual odometry, telecentric camera

1 INTRODUCTION

Positioning is one of the most important issues for mobile robots in mapping tasks and navigation. Odometry, a measurement method for determining a robot’s position and orientation by counting wheel rotation, is one of the simplest methods for estimating the position of wheeled mobile robots [1]. However, in a loose soil environment, such as that on the moon or Mars, it is very difficult to apply a conventional odometry method directly because of wheel slippage [2] [3]. Therefore, non-contact method offers the advantage of measuring the position of wheeled mobile robots in such environments.

A vision-based approach is an effective non-contact method for the positioning of mobile robots, particularly outdoors. Many vision-based navigation methods have been proposed since 1976, including that of Stanford Cart [4]. Recently, the Mars Exploration Rover (MER) succeeded in long-range
autonomous navigation using stereo vision-based visual odometry [5] [6]. The result proves that visual odometry works effectively in outdoor fields when a Global Positioning System (GPS) does not work.

Thanks to the progress of computational power, optical flow is a key technique in computer vision [7]. The optical flow technique was therefore considered for application to robot positioning by obtaining flow-images of the adjacent surface of the ground with a single CCD camera [8] [9] [10] [11]. The method is narrowly defined as “visual odometry”. Its advantage is that it can be used to estimate a robot’s position and orientation by detecting small ground features without using artificial or natural landmarks. For example, Nagai’s visual odometry system was successfully implemented on a mobile robot, and the system was validated on a concrete surface without an artificial pattern. However, in a loose soil environment, the results of the measurements from visual odometry were unreliable. That is because the distance between the camera and the ground varies when the wheels sink into the loose ground (e.g., Fig. 1) and the scale unit measuring the flow image changes to calculate robot’s velocity.

To solve the problem described above, we developed a visual odometry system using a camera with a telecentric lens [12]. The lens keeps the same field of view with a change of distance between the camera and the ground, so that it is applicable on loose soil. Furthermore, based on the developed visual odometry system and conventional gyroscope sensors, we developed a 3-dimensional visual odometry system and performed several experiments to evaluate its capability on our mobile robot testbed.

This paper is organized as follows: Section 2 is a description of problem statement, including a simple experiment with a conventional visual odometry which motivates this research. Development of a telecentric motion measurement system is introduced in Section 3. In Section 4, experiments of the telecentric motion measurement system mounted on mobile robots are described, and the performance of the proposed system is evaluated.
2 PROBLEM STATEMENT

It is obvious that visual odometry, a non-contact method, has an advantage for mobile robot positioning in slippery conditions. However, the method is sometimes unreliable when applied to small robots operating on loose soil because the wheels sink, which changes the scale of the images. Therefore some experiments were performed to determine the degree to which the measurements were affected by the wheels sinking in loose soil. Through the experiments, we confirmed that conventional visual odometry for small robots is not reliable enough on loose soil. In this section, we report on basic positioning experiments conducted with a conventional visual odometry system and explain the motivation for this research.

2.1 Conventional visual odometry system

To determine the degree to which the change in the image scale affects the accuracy of the odometry, we mounted a visual odometry system on the mobile robot.

Figure 2-(a) is a photograph of the visual tracking board [11]. It is a device used to estimate the translational velocity by tracking the flow of ground features with an NTSC camera. The device consists primarily of a video decoder, which converts the analog image signal from the NTSC to a digital image, SRAM, which stores images, and FPGA, which performs image tracking. It can measure up to a velocity of 96 [pixel/frame] in an arbitrary plane at the frame rate. The measured data is transferred via a serial connection. For an NTSC camera, we used a normal CCD camera (Watec WAT-902B), which has a horizontal angle of view of 24.2[deg]. The above visual odometry system was mounted on the mobile robot shown in the Figure 2-(b).
2.2 Algorithm of ground-pattern tracking

To track the ground-pattern for visual odometry, Nagai proposed a tracking algorithm that is robust in a natural colorless pattern [11]. The algorithm was validated on grass, carpet, and a straw tatami mat. Figure 3 shows an image of Toyoura sand.

A feature of the algorithm is to use a group of reference points instead of template blocks. The reference points have discrete location and solidly move according to image tracking. The movement of the image features between the two frames is obtained by calculating the interframe correlation of the group of reference points. It is not suitable to extract and track some objects in a video image, but it is effective to track the full image flow. In addition, it is suitable for FPGA-based logic to implement on a small board, as shown in Figure 2-(a). In our implementation, the number of reference points is 256; maximum velocity is from -31 to 96 [pixel/frame] (x-direction) and from -31 to 32 [pixel/frame] (y-direction). Details of the algorithm and implementation are described in [11].

2.3 Initial comparison experiment

We mounted the above visual odometry system on our mobile robot and conducted two simple experiments. The conditions were as follows.

- Circumferential velocity of the wheel : 3 [cm/sec]
- Traveling distance : 80 [cm]
- Ground : P-tile and soft soil (Toyoura-sand)

In soft soil, when the robot started moving, each wheel started sinking until it became stable. Finally, the subsidence of the wheel was 35[mm]. Figure 4 shows the estimated paths and the actual path, which is called “ground truth”.

The ground truth was measured by an optical instrument called “total station” produced by Nikon Trimble. It is a combination of an electronic theodolite (transit) and an electronic distance meter to detect the distance to a target corner cube. It also has an automatic tracking system of the target;
therefore it obtains a transition record of the target. The target corner cube is mounted at the center top of the robot. According to the Nikon Trimble catalog, the accuracy of the measurement of moving objects is less than 1[cm].

2.4 Discussion

In Figure 4-(a), it is obvious that visual odometry returns a very accurate position of the robot and is independent from wheel slippage. However, because of wheel sinkage, we confirmed the following two major problems.

One problem is the difference in scale. If the distance between the camera and the ground is fixed, the performance of the visual odometry is very good, which is confirmed in Figure 4-(a). However, because of changes in the distance between the camera and the ground, the accuracy of a robot’s position decreases, shown in Figure 4-(b). If the camera is mounted high enough, the effect of the sinkage of the wheel on the camera scale is relatively small. However, such situations are difficult for small robots. Furthermore, the ground pattern may not be detected with a high-mounted camera.

The other problem is the failure of tracking. When the soil parameter changes, the wheels go up or
down, and a the distance between the camera and the ground changes. During this process, the hue of the ground image zooms in and out, which prevents correct matching for visual tracking. Figure 5 shows the transition of a robot’s velocity measured by our visual odometry. In the first 4 seconds of the figure, the velocity of the robot measured with the visual odometry system is unstable. We assume that the matching process failed because of the changes in the hue of the ground images.

The two problems described above motivated us to develop a new visual odometry system, which is described in the following sections.

3 DEVELOPMENT OF A TELECENTRIC MOTION MEASUREMENT SYSTEM

To overcome the problems defined in the previous section, we developed a visual odometry system with telecentric camera whose lens keeps the same field of view with a change of distance between the camera and the ground. The system is called a Telecentric Motion Measurement System. It consists of a telecentric camera (a CCD camera and a telecentric lens) and an FPGA-based visual tracking board which is shown in the previous section. Its architecture and initial performance tests are described below.

3.1 Design and development of our telecentric camera

It was very difficult to obtain a wide-area telecentric lens commercially, therefore, we developed our own object-side telecentric optical system. The parameters of our telecentric optics are described below.

Our objective was to estimate the position of a small mobile robot on loose soil. Its maximum velocity was set as 100 [mm/sec]. Using a standard CCD camera with a frame rate of 30 frames per second, a system is required to measure 3.33 [mm/frame]. Our visual tracking board has the capability to measure 96 [pixel/frame], and the effective pixels of the longitudinal/horizontal axis of the image is 512 [pixels]. Therefore, the distance from the center to the edge of the viewing area \( W/2 \) is calculated as follows.

\[
W/2 = \frac{3.33 \times 512}{96} = 17.78[mm]
\]

This means that the minimum diameter \( W \) of the lens should be larger than 17.78 \times 2. To keep on the safe side, we selected a commercial aspheric surface convex lens (aperture = 50[mm], focal length = 90.8[mm]), manufactured by Ikuta Seimitsu Co., Ltd. When the lens is located 90.8 [mm] away from the origin of the field angle of the camera lens, it configures the telecentric optical system. If the focal length is shorter, smaller telecentric optics can be configured. However, in this case, the camera-side lens must be a wide-angle lens that generates a large deformation. The focal length was determined by trial and error.
On the other hand, the camera lens is required to have a field angle as \[ \tan^{-1}(17.78/90.8) \times 2 = 22.16[^\circ] \]

, therefore we chose EMVL-MP1214 (focal length = 12.0[mm], horizontal field angle = 24.2[deg]) made by Misumi Group Inc. as a standard c-mount camera-side lens.

Due to the above parameters, the distance per pixel (resolution) is calculated as 0.0723[mm]. According to our initial experiment, it has a constant field of view regardless of the distance between the lens and the target from 3.0[cm] to 13.0[cm]. Figure 6-(a) shows a schematic of the developed telecentric camera that includes the CCD camera and lens layout, and Figure 6-(b) shows our hand-made telecentric camera.

Finally, our conventional camera shown in the previous section was replaced from the telecentric camera to conform a telecentric motion measurement system. We also mounted 8 white LEDs at the side of the aspheric lens to gain a lightness contrast of an image.

3.2 Initial performance tests

To evaluate the measurement accuracy of the developed motion measurement system, which contains the above-described telecentric optics, simple experiments were conducted. We attached the telecentric camera to the tip of a manipulator arm. The motions of the camera were generated by controlling the arm, which resulted in very accurate position control of the camera. Figure 7 is an overview of the experimental setup.

Figure 8 shows three images of the grid sheet obtained by the telecentric camera with different distances from the ground. The value of the distance (z-axis) was changed to 30 [mm], 80 [mm], and 130 [mm]. Each grid size is 10[mm] squares. The image scales do not change with various distances from the camera. This is the most important feature for the telecentric motion measurement system.

The camera was then moved in a short distance over a conventional carpet pattern using the manipulator arm at an average velocity of 15 [mm/s]. Performance tests for the translational motion of the
telecentric camera were conducted in the following three patterns:

**Pattern 1**: Moving the camera from (-50, 0, 30) to (50, 0, 30)

**Pattern 2**: Moving the camera from (-50, 0, 130) to (50, 0, 130)

**Pattern 3**: Moving the camera from (-50, 0, 30) to (50, 0, 130)

where the coordinate axes are shown in Figure 7. The motion patterns were repeated 20 times, and the maximum error of length and maximum standard deviation were calculated.

Table 1 shows the results of the experiment. The results indicate that the maximum measurement error was 2.36 % and the maximum standard deviation was 0.47 %. We conclude that the errors of translation of the proposed system are small enough for the measurement of a mobile robot’s transition.

### 3.3 Implementation of visual odometry for mobile robots

In order to apply the telecentric motion measurement system to a visual odometry for our mobile robot, two issues have to be resolved. The first is how to compensate for an instration offset of the camera to
Table 1: Performance of a visual tracker

<table>
<thead>
<tr>
<th>Pattern / Orientation</th>
<th>Error %</th>
<th>Std. deviation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern 1 / x-axis</td>
<td>2.26</td>
<td>0.16</td>
</tr>
<tr>
<td>Pattern 1 / y-axis</td>
<td>1.26</td>
<td>0.34</td>
</tr>
<tr>
<td>Pattern 2 / x-axis</td>
<td>0.46</td>
<td>0.07</td>
</tr>
<tr>
<td>Pattern 2 / y-axis</td>
<td>2.10</td>
<td>0.47</td>
</tr>
<tr>
<td>Pattern 3 / x-axis</td>
<td>0.56</td>
<td>0.07</td>
</tr>
<tr>
<td>Pattern 3 / y-axis</td>
<td>2.36</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Figure 9: Compensation of an instration offset of the camera

obtain translational velocity, and the second is how to realize three-dimensional odometry.

A superficial translation velocity for the sensor is generated by a summation of a translational velocity and a rotational velocity of the robot body. Therefore the superficial translation velocity is compensated for by a measurement of the rotational velocity (Fig. 9). To measure the rotational velocity, we used a gyroscope to detect the yaw angle on the robot. The translational velocity of the robot body \((v_{bx}, v_{by})\) was then calculated using the following equation:

\[
\begin{align*}
v_{bx} &= v_{cx} + l \omega_b \sin \theta \\
v_{by} &= v_{cy} - l \omega_b \cos \theta
\end{align*}
\]

\(v_{bx}, v_{by}\) are the velocities in the X direction and the Y direction, respectively, obtained by the telecentric motion measurement system, \(\omega_b\) is the angular velocity of the robot body, and \(l_x\) and \(l_y\)
are, respectively, the offset lengths of the camera in the robot coordinate system. For our robot, \( l_x \) is set as 200 [mm], and \( l_y \) is set as 0 [mm].

For the latter issue, we use three gyroscopes for the measurement of the roll, pitch, and yaw angles of the robot body. Then, \( v_x \) and \( v_y \), obtained by the Equation (2)-(4), are translated into an inertial coordinate system using the Euler angle conversion. By calculating the integration of the velocities in the inertial coordinate system, the robot’s position and attitude are calculated three-dimensionally.

The above implementation was performed on our mobile robot testbed, and several evaluation experiments were conducted. They are shown in the following section.

4 Experiments

To confirm the validity and the limitation of our developed system, we performed the following three experiments.

Experiment 1 Checked robustness against change of distance between camera and the ground

Experiment 2 Checked maximum velocity of the measurement

Experiment 3 Performed outside tests

4.1 Experimental setup

We used both small and middle-size rover testbeds, as shown in Figure 10. Both rovers have the same structure. They are four-wheeled robots that were developed by our research group. Each of the wheel has two motors, one for driving and one for steering, and each can be controlled independently. The wheels are connected to the main body by a rocker suspension. The testbed (a) is 55 centimeters in length, 38 centimeters in width, 30 centimeters in height, and weights about 13 kilograms. The testbed
In both testbeds (a) and (b), a telecentric camera and a normal camera were mounted in the front/rear center of the robot. The distance between the normal camera and the ground was set to keep the same image as that of the telecentric camera when the wheels were on a hard floor.

To measure a robot’s ground truth, we use the total station introduced in Section 2.3.

We used testbed (a) for Experiments 1 and 2 and testbed (b) for Experiment 3.

4.2 Experiment 1: Checking robustness against the change of distance between the camera and the ground

In the first experiment, we ran the rover testbed (a) for 80 [cm] on an 8[deg] tilted sandbox that contained Toyoura sand (very fine-grained sand).

We conducted this experiment in three times. Figures 11-(a) and (b) show one of the comparisons of the measurement results between a telecentric camera and a normal camera. The measurement results
using a telecentric camera (red line) fit the ground truth (black line), but a large degree of error was noted when the normal camera was used. In the three experiments, the average error with the telecentric camera was 2.7 % (standard deviation is 0.38 %), and the average error with the normal camera was 53.1 % (standard deviation is 5.15 %). For reference, the average length of measurement results with the conventional wheeled odometry was 800 [cm], ten times larger than the ground truth.

In both cases, when the robot started moving, each wheel started sinking (Fig.12-(a)) until it became stable (Fig.12-(b)). The distance between the camera and the ground then changed from the initial condition to the final condition. Visual sinkage of the wheel was about 3.0[cm]. This means that the distance between the camera and the ground changed from 8[cm] to 5[cm], which indicates that the appearance of objects in its image is magnified 1.6 times. Therefore, the order of the error value is reasonable, and the telecentric camera works well in such conditions.

4.3 Experiment 2: Checking the maximum speed of the measurement

Theoretically, the maximum measurement velocity of the telecentric motion measurement system is 96 [pixel/frame], which is equal to 208 [mm/sec]. To confirm the value, we performed one simple experiment to confirm the maximum measurement velocity.

On the flat sand-box filled with Toyoura sand, we changed the reference velocity of the wheels. We also recorded the measurement velocity by the telecentric motion measurement system and its actual velocity by the total station, introduced in Section 2.3. Finally, we compared the both profiles of velocities.

The results of the above experiment indicated that the telecentric motion measurement system measured steadily up to 100 [mm/sec], and it could not measure over 110 [mm/sec]. It did not reach the theoretical value. We assumed that the major reason was a lighting condition: it was not enough to cover whole area by 8 white LEDs. The assumption was confirmed by an another experiment in which the system measured around 140 [mm/sec] in case of existing an external light on a carpet floor. In our current configuration, it satisfied the conventional planetary rover velocity. Therefore we did not add an additional LEDs.

4.4 Experiment 3: Performance test in long-distance navigation

We conducted outside experiments using a middle-sized rover testbed (Fig.10-(b)) at the seashore in Miyagi Prefecture, Japan (Fig.13-(a)). In the experiments, we set the rover’s velocity as 40 [mm/sec]. We performed several test runs in various conditions, and the total navigation length of the experiment was about 100 [m]. One of the measurement results is shown in Figure 14. In this case, the navigation length was about 20 meters, and the first 6 meters was a gentle up-slope. According to the graph, the measurement result by the visual odometry with a normal camera includes a large degree of error. On the other hand, the measurement result by the telecentric motion measurement system corresponds with the ground truth.
Table 2: Performance in the outdoor experiment

<table>
<thead>
<tr>
<th>Odometry method</th>
<th>Error in x-axis %</th>
<th>Error in y-axis %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheeled odometry</td>
<td>24.8</td>
<td>11.3</td>
</tr>
<tr>
<td>Visual odometry with a normal camera</td>
<td>18.8</td>
<td>10.7</td>
</tr>
<tr>
<td>Telecentric motion measurement system</td>
<td>0.1</td>
<td>2.4</td>
</tr>
</tbody>
</table>
Figure 14: Comparison of experimental position on loose sand for long navigation

[13]. Now, it appears to be a reliable and requisite system for research on planetary rovers. However, based on our current implementation, it seems difficult to apply such a system to faster robots. This, of course, depends on the computational power, ground patterns, and diameter size of the aspheric lens. In future works, we would like to develop a smaller system and a faster measurement velocity.

REFERENCES


