The Climbing Sensor: 3-D Modeling of a Narrow and Vertically Stalky Space by Using Spatio-Temporal Range Image

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***Abstract*— In this paper, we propose a novel type of 3-D scanning system named 'Climbing Sensor'. This system has been designed for scanning narrow and vertically stalky spaces, which are hard or extremely inefficient to scan by commercial laser range scanners due to their dimensions and limitation of FOVs. The climbing sensor equips a platform with two line scanners on a lift, and they scan through the whole target while the lift moves downwards along a ladder. One scanner is for scanning the target, which scans horizontally as the lift moves vertically, and the other scanner is for localizing the platform, which scans vertically. By using spatio-temporal range image acquired from the vertical scanning, we can accurately calculate the speed of the moving platform, with which a correct 3-D model can be constructed from horizontal scans. We applied this scanning system to the Bayon Temple in Cambodia as a part of our digital archiving project of cultural assets. The scanning results proved that the system gives a sufficiently accurate 3-D model and the effectiveness of our proposed system and speed estimating process.**

***Index Terms*— 3-D modeling, Cultural assets, Laser range finder, Spatio-temporal range image, Vertical movement mechanism, Lift and ladder**

I. Introduction

Due to the great improvement in computer processing ability, research on image processing and computer vision are recently gaining much attention. Among them, scanning an object in the real world to create its 3D model is one of the best-known topics in computer vision. Geometric data with high accuracy from a laser scanner broadens the target of scanning to many fields, such as academic investigation and entertainment.

One of the main application areas of modeling an object is in valuable cultural assets constructed years ago. These constructions deteriorate due to exposure to natural weathering and natural disasters such as earthquakes. There is a strong need to guard such cultural assets and save them from further harm, and an accurate model of the assets is necessary for restoration. 3-D modeling of cultural assets and historically important objects has been of strong interest worldwide as seen in [13]. We have modeled cultural assets such as The Great Buddha in Nara and Kamakura[2], Kohmokuten Statue, Fugoppe Cave, etc.

Currently, we have been scanning the whole geometry of the Bayon Temple[11] in Angkor Thom, in The Kingdom of Cambodia, using several commercial sensors such as Cyrax 2500[12] and our original sensors such as the Flying Laser Range Sensor[5]. Most of The Bayon Temple has been modeled with the use of these sensors, but there still remain many holes that are hard or extremely inefficent to scan by ordinary commercial laser range sensors due to their limitation of FOVs and the narrowness of the place to set them compared to their dimensions. Z+F IMAGER[22], which spherically scan the surroundings, can scan narrow areas without being confronted with the FOV problem, however this sensor causes another problem that the density of range point becomes extremely dense or sparse from scanning area to area. Additionally, because its scanning principle is phase-shift detection, the problem of distance ambiguity also occurs. To solve all these problems, we developed a novel scanning system, **'Climbing Sensor'**, which enables us to scan in such narrow areas with uniform range point density. The climbing sensor equips a platform with two line scanners on a commercial lift, and they scan through the whole target while the platform moves upwards or downwards along a ladder. Moreover, though the moving speed of the platform varies from case to case according to the setting situation of the ladder, we automatically estimate the speed by using spatio-temporal range image, our original notion, which is derived from one of the two sensors and does not accumulate error in the estimation phase.

The paper is organized as follows: related works are described in II; the system configuration of the climbing sensor is presented in III; Spatio-temporal range image is introduced in IV; our algorithm to obtain an accurate 3-D model is described in V; modeling results through our proposed approach are shown in VI; and our conclusion and future work is shown in VII.

II. Related Works

There are several related methods that scan a target from a moving platform. One example is a sensor that uses a helicopter[3][17]. These methods repeatedly scan the target in line while the platforms move, and localize the position of the helicopter by external hardwares such as GPS. The difference between the two methods is whether the algorithm uses the line scan itself to locate the position of the helicopter. The problem with these methods is the minute periodic distortion in the range image due to the vibration of the helicopter, and therefore there is a need for compensating for the distortion. Another problem is that when trying to model cultural assets, a scanning method using a helicopter seems inadequate. Also, in our case, when there is little space for scanning, it is impossible to use the helicopter as a moving platform.

Another method that is similar to using a helicopter is one that uses a flying balloon[5]. In this case, the speed of the platform movement is slower compared to the helicopter, and therefore areal scanner is equipped. This sensing system is designed to scan targets that become occluded when using a sensor fixed on the ground. The advantage of using a flying balloon is that correction of the data becomes simpler because the speed of the platform becomes slower than the helicopter. The problem of this sensor is same as above: it is inappropriate to use around cultural assets. Also, there needs to be broad space over the target for flying the balloon, which is not available in our case.

When modeling much larger targets such as cities, the use of a vehicle as the moving platform can be considered. One way to localize the platform is by using external devices such as GPS or inertial sensor[21].

For gaining a more accurate location under general conditions, several methods to use two line scanners are also known to be practical: for example, one scanner is used to scan the whole target while moving and the other is used to scan in the direction parallel to the movement. By comparing the consecutive scans that are parallel to the movement, the relative movement of the platform can be derived. This kind of approach always faces a problem that the error accumulates as repeated relative estimation of the movement is made through the whole process. In [7][8], for example, where the estimation variable is the horizontal position, the problem is solved by correcting horizontal scans by matching a photo image acquired from an airplane, which has accurate edges of the buildings in the city. In the field of mobile robotics, the problem is improved by using Extended Kalman Filter, which is known as simultaneous localization and mapping, and has been studied for over 15 years[9][18]. Recent research has focused on extending its approach to larger environments with a speeding up algorithm[10][14][15].

From the perspective described above, and also in our climbing sensor, scans parallel to the moving direction, which is not horizontal but vertical, are considered. However, the way to localize the platform is our original one: the use of spatio-temporal range image[4], which is novel, simpler, and suited to our scanning situation.

TABLE I
SPECIFICATIONS OF THE NOBITEC LIFT

Maximum weight to ascent	100kgf
Maximum height	3200mm
Electric source	AC100V 50/60Hz
Electric power consumption	870W
Speed of ascension	25m/min (0.417m/s)
Dimensions	H4380 × W1210 × D509mm
Manufacturer	Medicom Corporation

TABLE II
SPECIFICATIONS OF THE LMS200 SCANNER.

Scanning principle	Time of flight, Line-scan
Scanning frequency	37.5Hz
Scanning angle (FOV)	100°/ 180°
Angular resolution	0.25°/ 0.5°/ 1.0°
Resolution	10 mm
Systematic error	± 15 mm
Laser class	1
Scanning range	80 m
Weight	4.5 kg
Dimensions	L156 × W155 × H210 mm

III. System Configuration of the Climbing Sensor

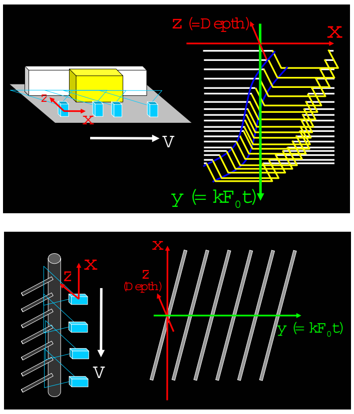
To quickly scan a space without enough space for ordinary commercial sensors, we used a commercial lift equipped with a telescopic ladder (Medicom's Nobitec Lift NPL-4200[16]) as a moving platform. By using this, the range sensors can move up and down in a narrow space, and we named the new sensor **Climbing Sensor**. The source of power is an electric motor connected to a winch. The specifications of the lift are shown in Table I.

First, we arranged two SICK sensors (LMS200[19]) perpendicular to each other. The specifications of the LMS200 sensors are shown in Table II. The reason that we used the LMS200 is for its light weight, compactness, and wide scanning angle (FOV) with sufficient scanning frequency compared to the speed of movement of the platform. One scanner was placed horizontally to the moving direction, which is vertical, and the other was placed parallel to the moving direction. The appearance of the two scanners is shown in Fig. 1(a).

The ladder of the climbing sensor is set against a wall, and the lift moves the platform upwards or downwards while two scanners are running. Since LMS200 sensors are line scanners, the horizontal scan can measure the whole object through the movement of the lift, and the vertical scan could be used to obtain temporal transition of the two sensors. The composition of the climbing sensor is shown in Fig. 1(b). Both of the LMS200 sensors move together by the winch attached to the lift, and according to the specifications of the lift, the speed of the movement is noted at 25m/min. However, the speed defined in the specifications seems inaccurate since the lift is set against the wall,the inclination of the lift varies from case to case, and the power source from a power generator may not necessarily be stable.

(a) (b)

Fig. 1. (a) Two LMS200 scanners attached to our platform. (b) An overview of the climbing sensor.



(a) (b)

Fig. 2. A basic notion of spatio-temporal range image.

With the use of the vertical scans we will be able to attain more accurate speed of the sensor movement.

This configuration solved the problem of the lack of space for scanning since the small platform moves vertically with enough horizontal FOV and uniform point density, and since the size of the lift itself is also less space-consuming.

IV. Spatio-Temporal Range Image

Here we propose a notion of spatio-temporal range image and describe its features and uses. Spatio-temporal range image is a kind of range image composed of a set of line-scanning range data. For example, when the scanning platform equipped with a scanner that repeats line-scanning to a horizontal direction moves horizontally, spatio-temporal range image can be acquired by placing its geometric scanning results next to each other with appropriate constant intervals as shown in Fig. 2(a). In the same manner, when the scanning platform equipped with a scanner that repeats line-scanning to a vertical direction moves vertically, spatio-temporal range image can be acquired in the same way as shown in Fig. 2(b).

Spatio-temporal range image has some interesting features. It simultaneously represents the spatial characters of the targeted scene, which can be represented as x in Fig. 2, and the temporal continuity of the movement, which can be represented as y. In other words, by looking at the spatio-temporal range image along the y axis, one can get the idea of how the sensor was moving in continuous time. Additionally, range points in the spatio-temporal range image cluster and compose some planes in most cases, due to the overwrap of scanning line and the difference of depth of the targeted scene from place to place.

The second feature described above implies that it is easy to extract edges from spatio-temporal range image. By using the edge, the moving speed of the platform V can be calculated through the following equation

$$m = \frac{\Delta y}{\Delta x} = \frac{kF_0 \Delta t}{\Delta x} = \frac{kF_0}{V} \quad (1)$$

where m is a slope of the edge and x-y-z coordinate is defined as Fig.2, i.e. x is a scanning direction, z is a depth, O is a center of the laser source, F_0 is scanning rate of the sensor, and k is an interval between each scan in placing them next to each other along a temporal axis. Note that spatio-temporal range image is represented by a Cartesian coordinate, not a polar coordinate.

Through this approach, we can localize the moving platform with the accumulation of the error as small as possible since the approach contains no matching process for each frame. If we consider localizing the position of the platform directly without calculating the speed of motion, the necessity of a matching process for each frame arises which brings forth the error accumulation problem. By having an extra step, we are able to disperse the error throughout the whole process, therefore more accurate model can be created.

V. Localizing Algorithm for 3-D Modeling

First, we present the outline of the algorithm to obtain the range image by the climbing sensor. The outline of the algorithm is as follows (Fig. 3).

1) Prepare a spatio-temporal range image using the vertical scans.
2) Delete useless data on the verge of the spatio-temporal range image.
3) Extract the edge using Sobel filter and vector.
4) Label the edges.
5) Obtain the gradient of the multiple edges by using principal component analysis.
6) Weigh the several gradients according to the length of the edges.
7) Calculate the average gradient.
8) Convert the gradient into speed of the sensor.
9) Calculate the self-position of the sensor.

We will follow these steps in the following.

A. Preparation of a spatio-temporal range image

Since the two sensors are moving vertically, data acquired from a vertical scan could be used to obtain temporal transition of the sensors. The LMS200 sensor is a line scanner, so if we place the data acquired from a vertical scanner next to each other, we will obtain spatio-temporal range image as shown in Fig. 4. The interval in the horizontal direction

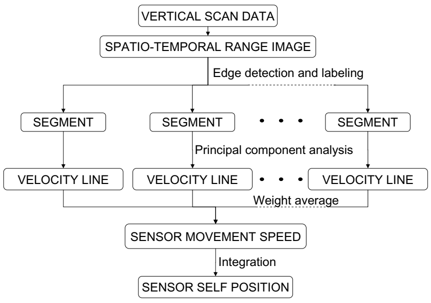


Fig. 3. Outline of the localizing process

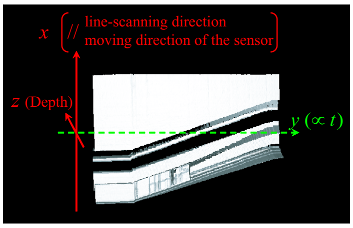


Fig. 4. Spatio-temporal range image

in Fig. 4 could be settled freely. As seen in this figure, the edges of the spatio-temporal range image can be distinguished easily. However, its verge contains useless data since the scanning took place not only while the platform were moving, but also before and after the movement. Although it is possible to detect the start point and end point of movement of the platform by equipping some finder or synchronization hardware on the ladder, we solved the matter with a software-based approach. As compared anteroposterior data, and if the majority of the data were similar, we determined that the sensor was not moving.

B. Edge extraction

After gaining spatio-temporal range image using data obtained only while moving, we extracted its edges. We used Sobel filter and vector to extract edges.

1) Sobel filter: The Sobel filter consists of two kernels that detect horizontal and vertical changes in an image. If both are applied to an image, the results can be used to compute the magnitude and direction of the edges in the image. The 3×3 Sobel kernels we used for horizontal and vertical are:

$$K_h = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix}, \; K_v = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} \tag{2}$$

The Sobel filter is usually used in intensity images, but in our case, instead of applying the Sobel filter to intensity value, we applied it to the Cartesian coordinates of the measured points. Since the data obtained from the sensor in one scan is represented in polar coordinates $\mathbf{p} = (r, \theta)$, we can easily convert them to Cartesian coordinates $\mathbf{c} = (x, y, z)$ using the following relationships.

$$x = r \sin\theta \tag{3}$$

$$z = r \cos\theta \tag{4}$$

The y coordinate value can be easily calculated from k, which represent the interval in which each scan is placed next to each other along the temporal axis. The Cartesian coordinates can be added suffixes like $\mathbf{c}_{m,n}$, where m describes the scanning-line number and n describes the point in a specific scan. In other words, m corresponds to the time, and n corresponds to scanning angle θ. We applied the sobel filter to $\mathbf{c}_{m,n}$ and the points around it: $\mathbf{c}_{m-1,n-1}, \mathbf{c}_{m-1,n} \cdots, \mathbf{c}_{m+1,n+1}$. By comparing the magnitude of the result with a threshold, we can extract edges.

2) Edge extraction using vectors: The use of vectors for extracting edges was considered next, since edge extraction was done in a range image. We paid attention to the angle between the four points adjacent to the point we are paying attention to. To locate the points to pay attention to, we used the polar coordinates, and used the Cartesian coordinates for creating the vectors. We calculated the angle between the two vectors $\mathbf{v}_1$ and $\mathbf{v}_2$, which are vectors pointing upwards and downwards from the point of attention, as seen in Fig. 5, where

$$\mathbf{v}_1 = \mathbf{c}_{m,n+1} - \mathbf{c}_{m,n}, \mathbf{v}_2 = \mathbf{c}_{m,n-1} - \mathbf{c}_{m,n} \tag{5}$$

The angle between the vector pointing left and right of the attention point is also calculated. If either of these two angles satisfy the following equation, we assumed the point to be an edge.

$$\frac{\pi}{12} < angle < \frac{11}{12}\pi \tag{6}$$

The angle could be easily derived by using the inner product of the two vectors, and dividing it by the length of the vectors.

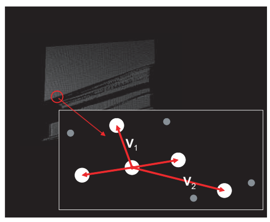


Fig. 5. Vectors to use for edge extraction.

3) Combination of two edge extractions: We used two edge extraction methods described above for higher accuracy in extraction. To avoid mistaken edges to be extracted and avoid edges missed in extraction, we set the threshold fairly low for detection and extracted edges that satisfies both of the conditions simultaneously.

Fig. 6. An example of area scanned by climbing sensor.

C. Caluculating the speed of the moving sensors

From the gradient of the edge, we can next calculate the speed of the moving sensors. Here we assumed that the speed is constant considering the mechanism of the lift and the ladder; the movement of the sensor is one-way and is moved by a winch connected to a motor in the lift. As stated above, we applied the speed obtained from spatio-temporal range image instead of the speed described in the specifications of the lift, which proved to vary from case to case and be inaccurate through the experiment.

First, we labeled the multiple edges obtained from Sobel filter edge extraction and vector edge extraction. After labeling we applied principal component analysis to each edge to obtain the primary component, from which we derived the gradient of the edge.

Principal component can be derived as a solution of the eigenvalue problem of covariance matrix $\boldsymbol{\Sigma}$ of range points:

$$\boldsymbol{\Sigma U} = \boldsymbol{U\Lambda} \tag{7}$$

$$\boldsymbol{\Sigma} = \frac{1}{N}\sum_{i=1}^{N}(\boldsymbol{x}_i - \bar{\boldsymbol{x}})(\boldsymbol{x}_i - \bar{\boldsymbol{x}})^T \tag{8}$$

where $\boldsymbol{x}_i$ is range point in the edge, $\bar{\boldsymbol{x}}$ is an average of $\boldsymbol{x}_i$, $\boldsymbol{U}$ is an orthogonal matrix composed of principal component vector, and $\boldsymbol{\Lambda}$ is an eigenvalue matrix.

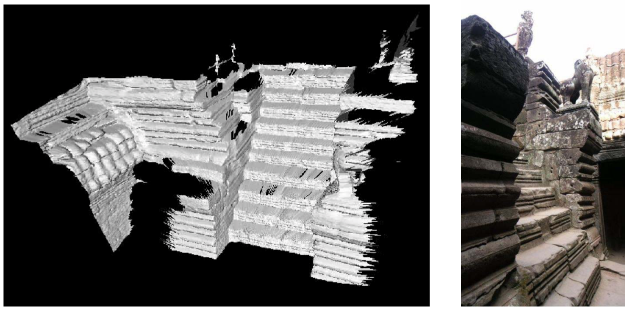
Estimated value of the speed is calculated from every edge. We weighted each value by their length and took an average considering that the longer the edge becomes, the more its error disperses, and the result will have higher reliability.

VI. Modeling Results

We used the climbing sensor to scan the Bayon temple in Cambodia. Our laboratory has been scanning the temple for a few years with several types of sensors; however, there still remain holes in the 3-D model. We used the climbing sensor to scan areas as shown in Fig. 6, which are hard or extremely ineffficent to scan with ordinary commercial laser range sensors due to their narrowness and their limitation of FOV.

Using the algorithms described above, we calculated the speed of the moving sensors, and used the estimated speed instead of 25m/min = 0.4167m/s which was indicated in the specifications of the lift to create an accurate 3-Dmodel.

Arranging the horizontal scans next to each other using the speed derived, we could obtain the 3-D model as shown in Fig. 7.



(a) (b)

Fig. 7. (a) The result of the model obtained from the climbing sensor by placing the horizontal scan in an interval calculated from the vertical scan. (b) Actual scene of the target.

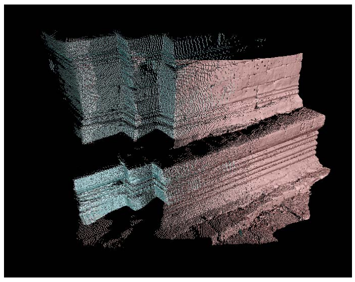


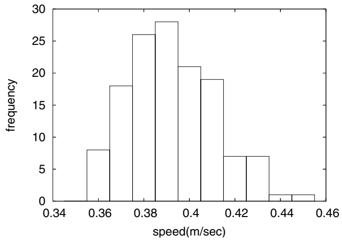
Fig. 8. The result of aligned range images: Red points represent the 3-D model obtained from a fixed sensor and light blue points represent the 3-D model obtained from the climbing sensor.

To show that the calculated speed was accurate, we aligned the range data obtained from the climbing sensor with a data obtained from a fixed range sensor using iterative closest point algorithm[1], [20]. As shown in Fig. 8, two range images were aligned without errors, and therefore the speed calculation can be said to be correct, since the accuracy of a fixed sensor is high enough.

Also, to clarify the effectiveness of the speed estimation process, we compared two scans with different values of calculated speeds. Since the ladder is set against a wall, its inclination and hence friction between the platform and a guide on the ladder varies from case to case, causing differences in the speed of movement of the platform. As Fig. 9 shows, the speed varies quite dramatically between different scans. Although the speed differs considerably, two range images corrected with different values of estimated speed align well, as shown in Fig. 10. Note also the difference between the calculated speed of scan 1, 2 and the speed specified in the figure. The speed is strongly influenced by the situation of the lift, but this result shows that the algorithm used leads to a correct speed regardless of the inclination of the ladder.

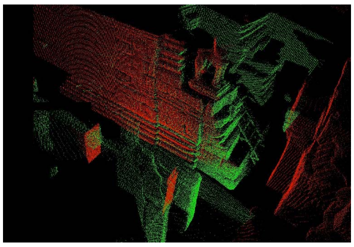
VII. Conclusion

In this paper, we proposed a new type of sensor named Climbing Sensor to scan areas too narrow for ordinary commercial sensors. While the localization of the sensor in



Avg. = 0.387 m/s   SD = 0.0190 m/s

Fig. 9. The histogram of estimated speed



speed (m/sec)	scan 1 (green)	0.3504
	scan 2 (red)	0.4081
	specification	*0.4167*

Fig. 10. The result of aligning two images with different values of calculated speed. The speed differs by about 5 cm/s, however, from the result when the alignment goes well.

a specific time is one of the general problems in remote sensing, by using a scan parallel to movement, we succeeded in obtaining accurate speed of the moving sensors on a ladder in most cases, avoiding error accumulation and dispersing them throughout the whole scan.

The results show that the speed is accurate since the alignment of the 3-D model with a model acquired from a fixed sensor corresponds well. Also, 3-D models obtaind by climbing sensor and corrected with different values of estimated speed match well, which proves the accuracy of the derived speed.

Although most of the range images align with other images quite well, some of them do not match with different images perfectly. This may be a result of failure in extracting the edge or failure in fitting a gradient to an edge. To solve these problems, as a future project, we are planning to align the images using parameter estimation registration[6]. By using this method, the correct speed of the moving sensor could be obtained under the condition that a range image including the same object from a fixed sensor is available.

Also, the algorithm used to calculate the speed of motion does not suppose the sensor to move at a constant speed. The main advantage of this algorithm is that the speed of motion can be calculated by the use of spatio-temporal range image, and therefore, it can be used to calculate the speed of a freely moving object. In the case of the climbing sensor, since the sensor is moving linearly and is moving by the power of a motor, assuming the speed to be constant seems reasonable. For future use, the implementation should be more generalized, where the moving platform moves freely.

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