구조화 조명 영상에 Dynamic Programming 을 사용한 신뢰도 높은 거리 측정 방법

Robust Depth Measurement Using Dynamic Programming Technique on the Structured-Light Image

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요 약

구조화 조명을 사용한 거리측정에 동적계획법을 적용함으로써 거리 측정의 정확성이 대폭 향상된 방법을 제안하였다. 구조화 조명을 사용한 거리 측정방법은 거리정보가 조명에 해당하는 화소의 위치에 의해 계산될 수 있다는 점을 이용한 것이다. 그러나, 이 구조화 조명 빛이 물체의 표면에서 흡수되거나 반사됨으로서 흐리거나 잘 보이지 않는 경우가 많다. 이 문제를 해결하기 위해서 본 연구에서는 동적계획법을 사용하였다. 동적 계획법을 위한 셀간 비용(cost)값은 화소 밝기 값의 역수를 사용하였으며, 상단과 하단에 각각 시작선 혹은 목표선을 설정하였다. 이 알고리즘의 장점은 동적 계획 법의 최적화 능력을 사용하므로, 구조화 조명선의 약한 흔적이나 부분적으로 절단된 조명선 위치도 잘 찾아낼 수 있다. 이 알고리즘을 사용하여 다양한 3 차원 물체를 복원한 실험 결과를 제시하였다.

Abstract

An algorithm for tracking the trace of structured light is proposed to obtain depth information accurately. The technique is based on the fact that the pixel location of light in an image has a unique association with the object depth. However, sometimes the projected light is dim or invisible due to the absorption and reflection on the surface of the object. A dynamic programming approach is proposed to solve such a problem. In this paper, necessary mathematics for implementing the algorithm is presented and the projected laser light is tracked utilizing a dynamic programming technique. Advantage is that the trace remains integrity while many parts of the laser beam are dim or invisible. Experimental results as well as the 3-D restoration are reported.

☞ keyword : Dynamic program(동적계획법), Optimal path(최적 경로), Structured light(구조화조명)

1. INTRODUCTION

In robot control, obstacle avoidance is one of the important problems to overcome. Distance measurement is the principal element for this desired capability. The stereo imaging-based technique [1][2], the time of flight of the sonar signal-based[3], and the structured lighting-based technique are major ones. The system developed and presented here bases on the structured light technique [4-9], which gives the high accuracy measurement. The system is composed of a single camera, a laser light projector and a rotating mirror [10][11]. The laser light is projected toward the rotational axis of the mirror, and then reflected onto the object. The camera

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catches the stripe light on the surface of the object through the same mirror. However, the laser light is often invisible due to surface absorption and reflection. In this paper, the location of thelaser light is tracked utilizing the optimality feature of dynamic programming. The dynamic programming (DP)[12][13] is a global algorithm to compute the optimal path through taking the local minimum operation at each node. It is also an efficient solution to find the optimal path that involves the combinatorial computational complexity[14]. DP can be applied to the problem of detecting the location of the light trace. The Cellular Neural Networks (CNN)is an ideal hardware model to implement the DP with simple analog processing of locally connected cells. The parallel processing algorithm of laser light tracking by the CNN has been addressed in references 15, 16 and 17.

2. Structured light Technique

Structured light is the projection of a light pattern (plane, grid, or more complex shape) at a known angle onto an object. This technique is very useful for imaging and acquiring dimensional information. Fig.1 shows the depth measurement system we proposed in [10][11] and its triangulation geometry. The system has a single vertical laser stripe projected to the rotating mirror, and then reflected onto the scene. The image formed by the same mirror is acquired by the CCD camera. Without losing the generality, we focus on the image formation of a single light point.

To derive equations in 3-D space, let ususe the cylindrical coordinate system with the mirror axis as the Z-axis. Assume that the light point T with coordinates (R, ϕ, Z) has its image on the CCD sensor at P = (P_X, P_Z) in the coordinates of image plan. In this figure, P_X is the distance from P to the camera optical axis. Using the property of similar triangles, one obtains

$$P_X : f = \delta_{t'} : D \tag{1}$$

Note that

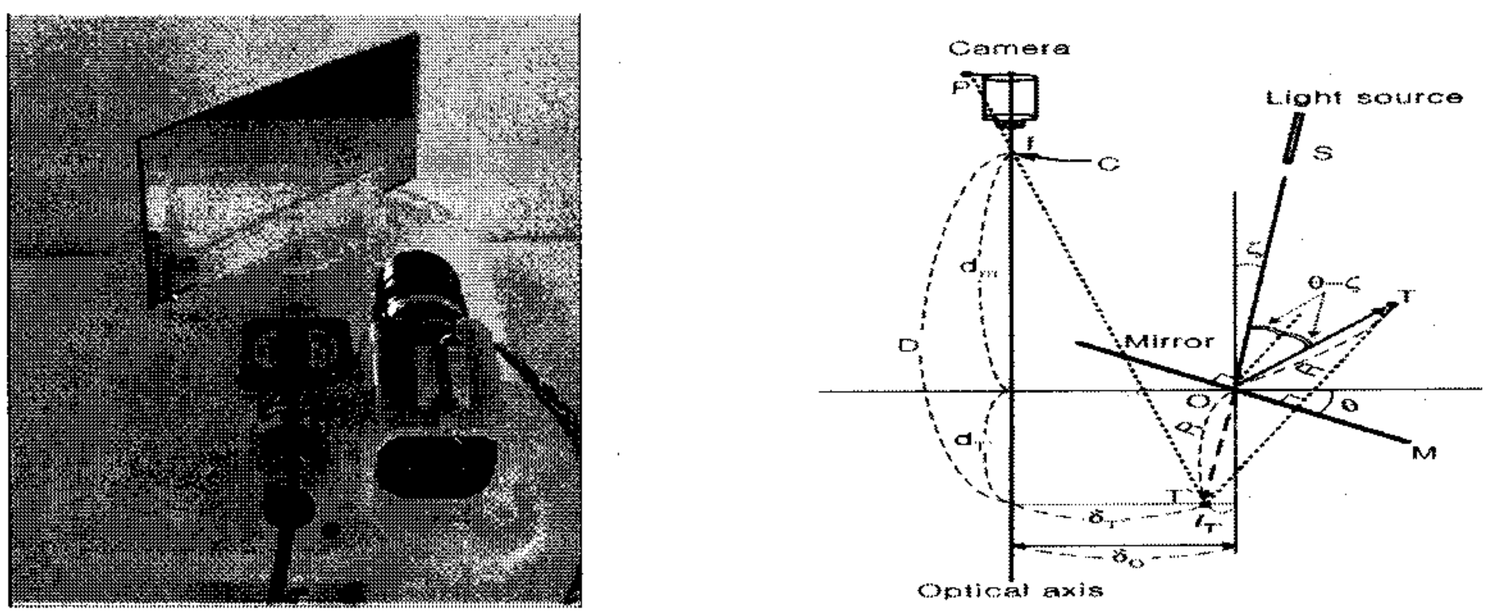
$$d_{T'} = R\cos\zeta,\ \ \delta_{T'} = \delta_0 - l_{T'},\ \text{and}\ \ l_{T'} = R\sin\zeta .$$

Hence

$$P_X(d_m + R\cos\zeta) = f(\delta_0 - R\sin\zeta) \tag{2}$$

Solving equation (2) for R gives

$$R = \frac{f\delta_0 - P_X d_m}{f\sin\zeta + P_X\cos\zeta} \tag{3}$$



(a) (b)

그림 1. 구조화 조명의 투사 및 반사에 의한 거리 측정 장치
(a) 개발한 거리측정장치 (b) 거리 측정장치의 구조도
Fig. 1.Illustration for the depth measurement with projection and mirror reflection
(a) proposeddepth measurement system, (b) schematic of the depth measurement system

The angle for the observed point T is , which is defined as the angle measured clockwise from the vertical axis to the line OT. This angle is determined by the direction of laser light and the mirror angle as

$$\phi = 2(\theta - \zeta) + \zeta = 2\theta - \zeta \tag{4}$$

From the triangular similarity, one can obtain

$$P_Z(d_m + d_t) = fZ \tag{5}$$

Dividing (5) by (2), the following equation can be obtained

$$P_Z / P_X = Z / \delta_T = Z/(\delta_0 - R\sin\zeta) \tag{6}$$

Solving the equation above for Z gives

$$Z = \frac{P_Z(\delta_0 - R\sin\zeta)}{P_X} \tag{7}$$

Note that the mirror angle is not involved in equation (3) for depth computation.

It is intuitionistic that different P_x represents different depth information as shown in Fig. 2. Small value of P_x means the object is far away, while big one means it is close quarters. The exactly depth "R" that involves more variable is given in equation (3). As referred before, the structured light technology is based on the trace of laser light in the CCD. If the intensity of laser light is much stronger than environmental illumination, it is possible to track the trace of laser light. However, problem arises when illumination is bright or the object surface is reflective. Unclear traces which encircled by white ellipses are shown in Fig. 2. Under such situations, it becomes difficult to get the trace of structured light by a simple method such as threshold. For those rows with the laser light undetectable, the depth ofthe corresponding point could not be computed.

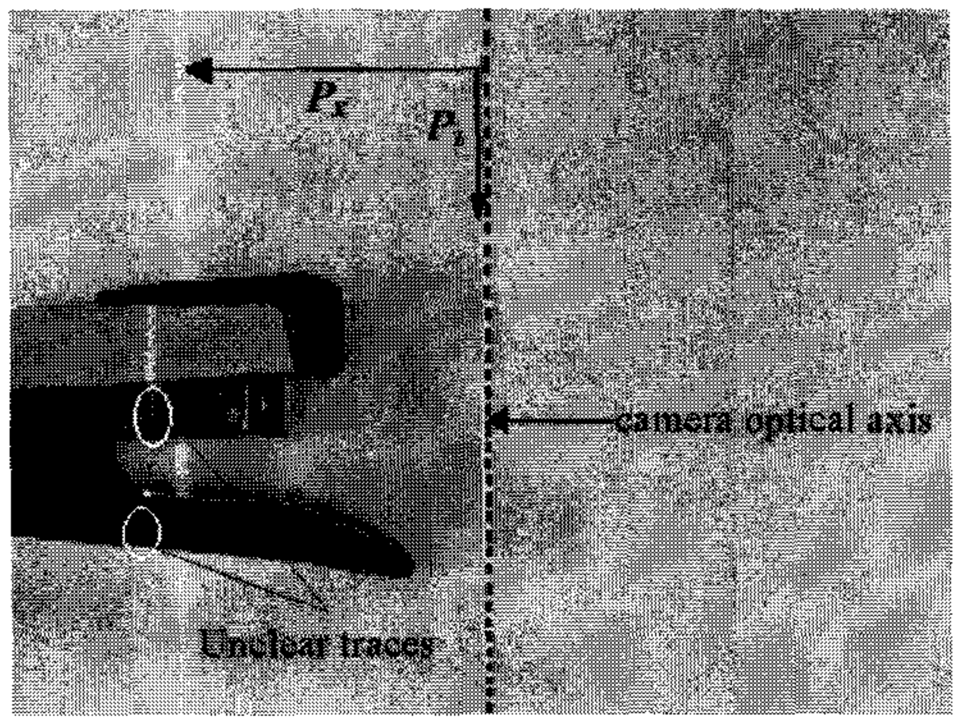


그림 2. 불 분명한 구조화 영상의 예
Fig. 2. Examples of unclear traces

To solve this problem, the algorithm based on dynamic programming is proposed and details are presented below.

3. Optimal Tracking of Structured Light Technology

3.1 Dynamic Programming

Fig. 3 illustrates the dynamic programming for optimal path finding.

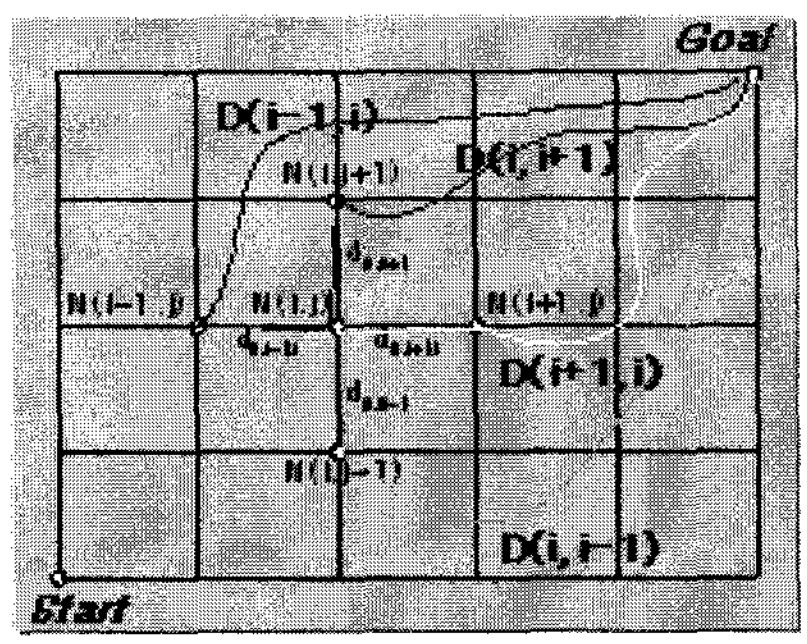


그림 3. 최적 경로 계산을 위한 동적계획법
Fig. 3. Dynamic programming for optimal path finding

Let D (i, j) be the shortest distance from node (i, j) and node (k, l) to the goal, respectively. Then, D (i, j) is computed utilizing D (k, l) as

$$D(i,j) = Min\{d_{ij,kl} + D(k,l), (k,l) \in R(i,j)\} \qquad (8)$$

$d_{ij,kl}$ is the shortest distance between node(i, j) and node (k, l). R (i, j) is the set of neighboring nodes around (i, j). Note that $d_{ij,kl}$ equals to zero if ij = kl. By setting the initial value of D at a goal (k,l) with zero and all others with a big value (much bigger than the shortest distance between the most far nodes), D(k,l) in equation (8) computes the minimum distance to the goal (k,l) at node (i, j). If an arithmetic cell is arranged to compute equation (8) at each node, the processing of equation (8) is confined to the local operation of minimum and summation.

For each node of the possible path, the one with minimum cost among the 4-connected neighboring ones will be selected to be the next node that the optimal path will pass. This process goes forward until the end points are reached.

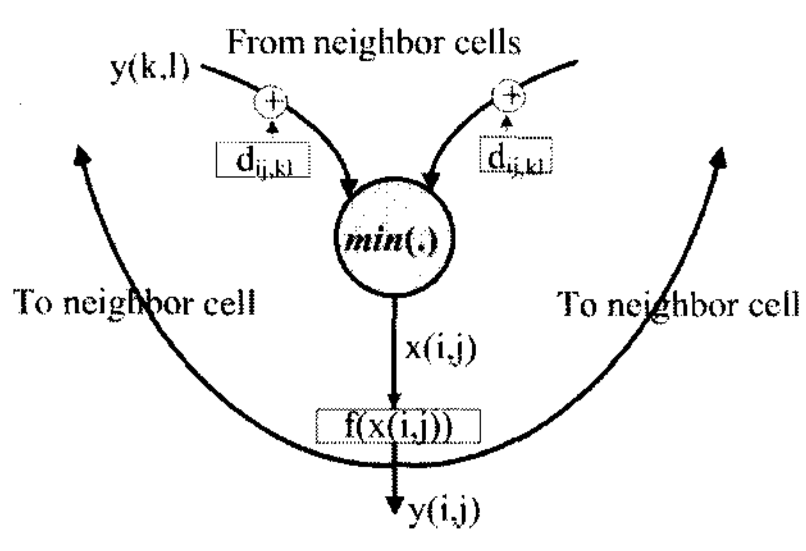


그림 4. 하드웨어로 구현을 위한 동적 계획법의 각 셀 모델
Fig. 4.Cell model of the DP for hardware implementation

The cell model to perform equation (8) is shown in Fig. 4. In this model, input isthe feedback from its own and neighbors' output. The nonlinear function of the minimum and the linear function of the subtraction are involved in this cell operation. The output function is assumed to be linear.

3.2 Light-trace tracking using dynamic programmin

A forward procedure begins at the starting line. It keeps substitutingthe output of each node with the minimum value from the 4-neighboring nodes until no node changes. Finally, the optimal path could be retrieved by a backtracking procedure with the same principle. The backtracking procedure begins at the end line, and then goes back to look for the neighboring node with the least cost until reaching the goal point. As a result, the nodes that the procedure goes back through form the optimal path.

In this system, "cost" is defined as the average intensity between two neighboring nodes based on 4-connectivity. (Since the simulation was done in computer which works serial, we just adopt 4-connectivity method. Actually, our algorithm performs better based on 8-connectivity, but it takes more computation as well as storage. However, we have already applied the algorithm in CNN hardware model that works parallel, and 8-connectivity is adopt in that circuit.) Without losing generality, the trace of structured light occupies a "path" with bigger intensity in general. To fit the dynamic programming strategy, an initialization for the original image is implemented to ensure that nodes occupied by structured light possess smaller "cost". Meanwhile, the cost between pixels along the whole bottom line in the image is assigned with 0 because it is unpredictable which one will be the end point.

The backtracking starts from the bottom of the image array, since each node in the last line will hold the same value after the forward procedure. Only the node that satisfies equation (8) will be selected and labeled, and then the other ones that fulfill the same relationship will be selected expansively. Once any node in the top line is picked out, the backtracking stops, and hence, each node that has ever been passed will be labeled. As a result, the trace of structured light will be obtained by plotting each labeled node.

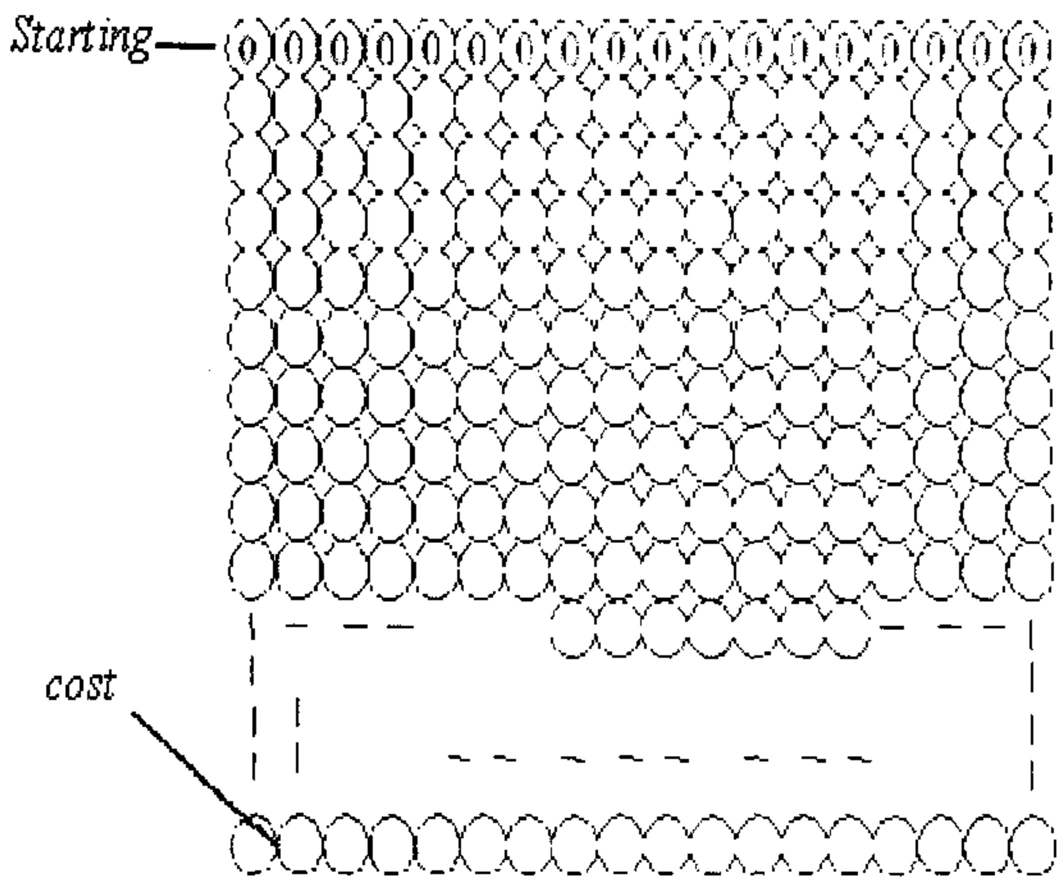


그림 5. 전방향 처리를 위한 초기화
Fig. 5.Initialization for forward procedure

The complete procedure starts from a preparative initialization followed by cost assignment. cost in the vertical direction is proportional to the trace of laser light and smaller in the horizontal orientation. The cost between nodes in the bottom and top is set to 0. The goal is set to the top line of the array and the starting point is the line at the bottom.A forward parallel processing of cost accumulation is then performed. The accumulated cost field is used for the backtracking process to retrieve the trace of laser light. The complete work is described in the following:

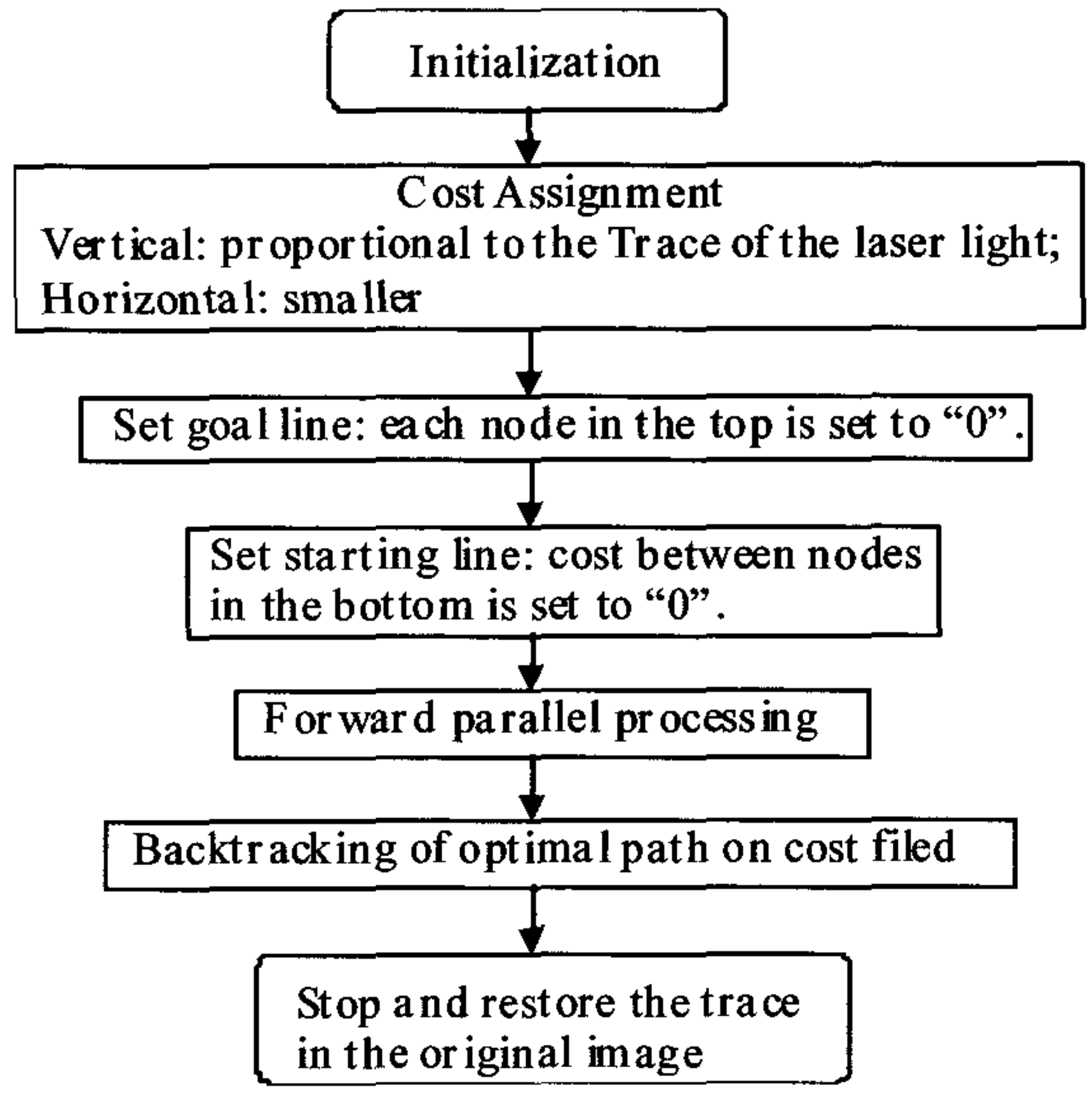


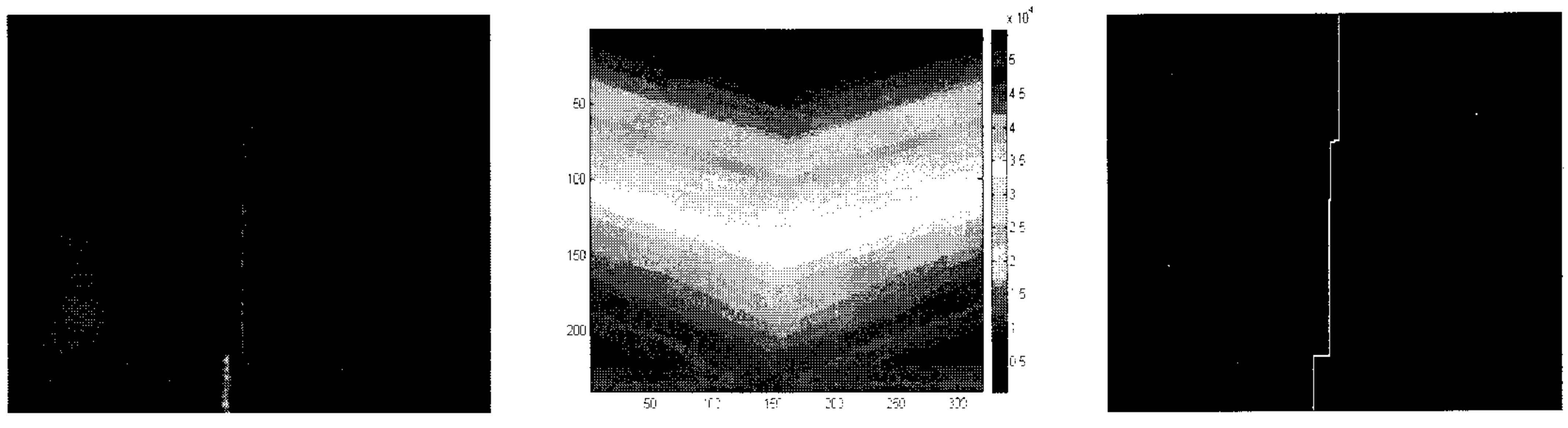
그림 6. 구조화 조명 위치 계산을 위한 알고리즘
Fig. 6. Tracking algorithm of the structured light trace

4. EXPERIMENT

In this section, experimental results are reported. The output of the laser projector is 3mw and a CCD cameral (512×480 8-bit pixels) is used. The distance d_m and δ_0 are set to 15cm and 8cm, respectively.

4.1 Structured Light Trace with Dynamic Programming

A vertical laser light is used to scan over the scene to obtain the complete depth information. Tracking the laser light trace is a necessary step. Fig. 7(a) shows one image grabbed while the camera was equipped with a filter. Note that the measurement was done in an environment with lighting at about 400 LUX. The image includes the object, whose part of the projected light is almost invisible. Even though, the final result proves that



(a) (b) (c)

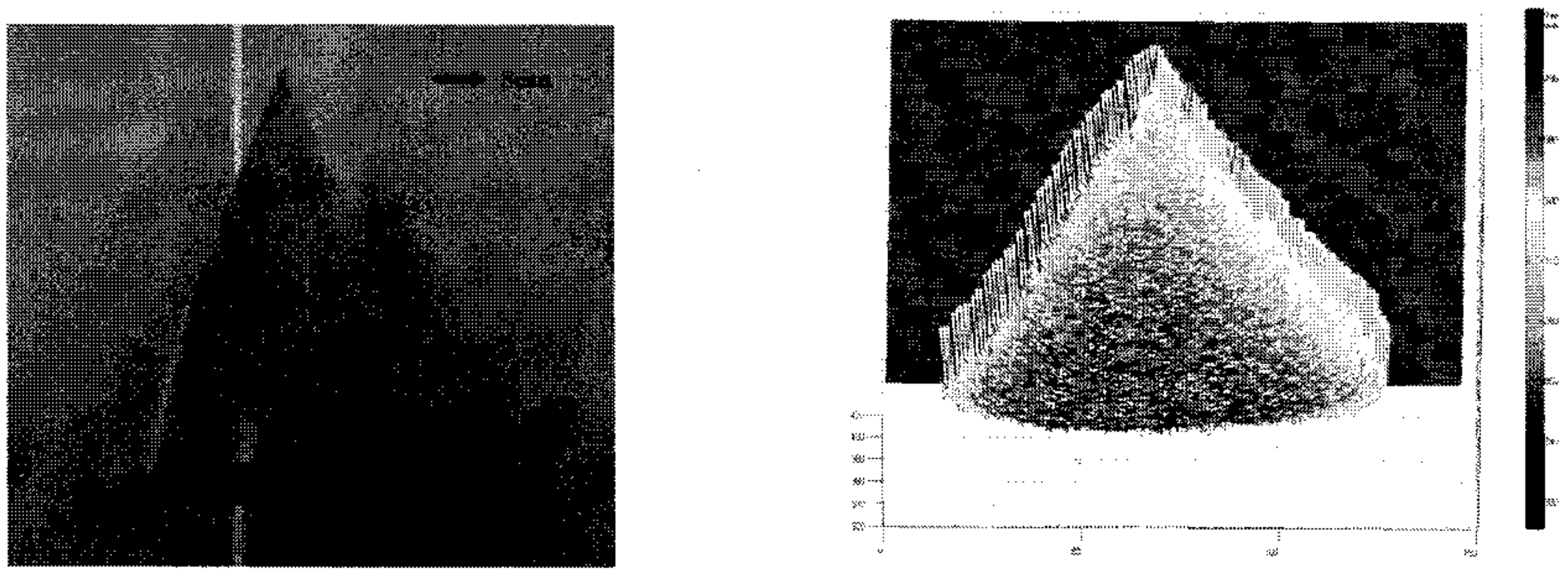
그림 7. 동적계획법에 의한 조명위치 추적 예 1.
(a)필터링을 거친 영상 (b) 전향 처리 결과 (c) 본 알고리즘에 의해
Fig. 7.Track the trace of structured light with DP
(a) filtered image, (b) result after forward procedure, (c) final result of structure light trace

the proposed algorithm works well in such cases. Nevertheless, the result(in Fig. 7(b)) after the forward procedure clearly shows the outline of optimal path; different colors in this figure represent different output values in the image. The color bar helps to distinguish the range for color distribution. Note that the final track in Fig. 7(c) covers the laser light in the original image.

4.2 Shape Restoration in 3-D

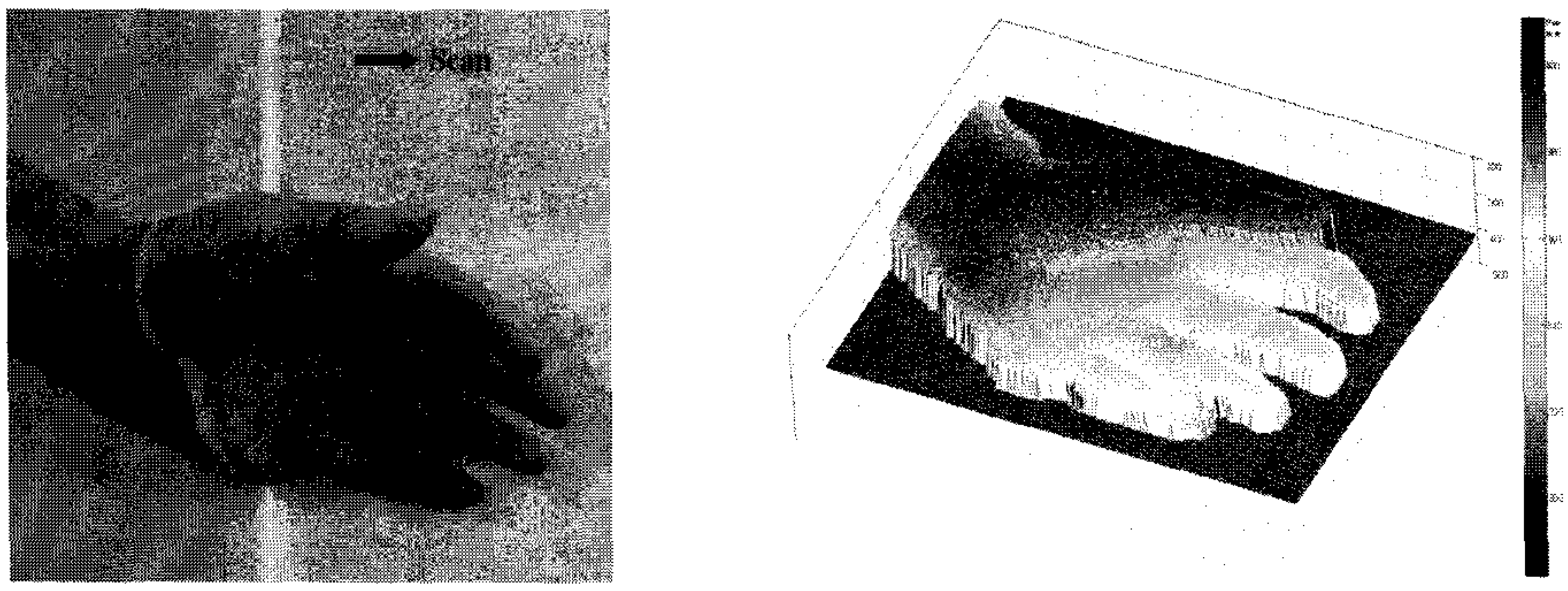
The 3-D measurement has been done to restore the object surface. Fig. 8(a) shows a cone measured by our equipment. Fig. 8(b) is the restored shape of the object with the use of our algorithm. The surface is precisely restored. Different depth is represented with different colors that change from navy blue to crimson.

Another shape (a hand) with more details, is shown in Fig. 9(a). The corresponding 3-D restored shape is shown in Fig. 9(b). Many details like the small changing in palm and fingers are preserved.



(a) (b)

그림 8. 제안한 방법에 의한 물체의3-D 형상 복원 예 1 (a) 테스트에 사용한 콘 형상 (b) 3-D 복원 형상
Fig. 8. 3-D restored example 1 with the proposed algorithm (a) cone for testing., (b) 3-D restored shape.



(a) (b)

그림 9. 제안한 방법에 의한 물체의 3-D 형상 복원 예 2 (a) 테스트에 사용한 손 형상 (b) 3-D 복원 형상
Fig. 9. 3-D restored example 1 with the proposed algorithm (a) hand for testing, (b) 3-D restored shape.

4.3 comparison with existing method

One hundred fifty sample points are random selected from the object surfaces that are restored with and without DP, respectively. As shown in Fig. 10, the green diamond points are samples from surface restored with DP, while the black circle ones are those restored without DP. Most samples locate within the range from -5 to +5 millimeter. The cluster of green points is near the no error line. Black points, however, are spread into a wider range. Those black points with big errors are points with laser light undetectable. The depth measurement is more precise with our algorithm there is a 30% improvement in the precision.

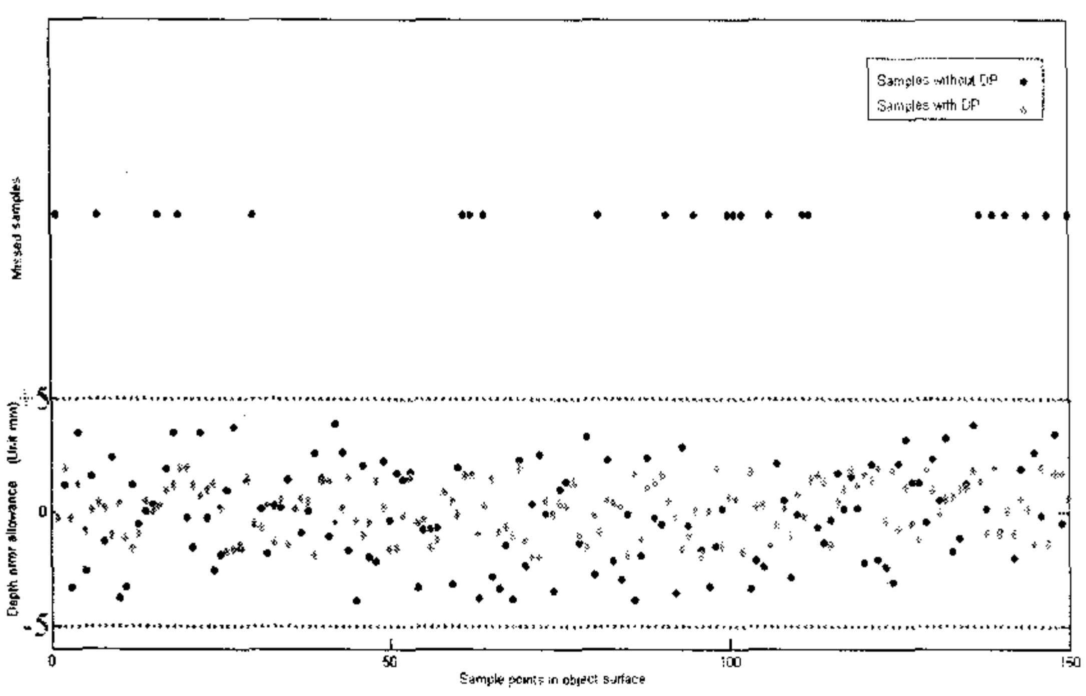


그림 10. 선택된 샘플들 간의 비교
Fig. 10. Comparison of selected samples.

5. CONCLUSION

In this paper, a depth measurement system using structured lighting is presented. To resolve the potential problem caused by surface reflection/absorption and bright environmental illumination, an algorithm based on dynamic programming (DP) is proposed for tracking the trace of structured light. The algorithm has utilized the optimal feature of DP, which consists of a forward procedure and backtracking. It computes the "cost" iteratively from the bottom to top, and then tracks the minimum nodes to determine the light trace. From the trace of structured light, depth information can be computed. Depth of the whole object is obtained by scanning the laser light over its surface.

Preliminary experimental results indicate that the proposed method can successfully restore depth information for bigger area of the scene, showing more solid performance compared to those obtained without using the algorithm.

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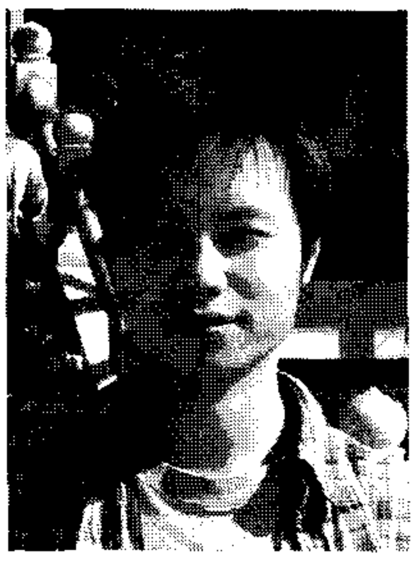

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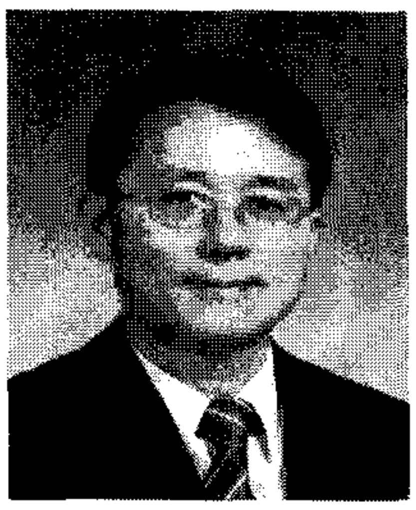

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