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DETECTION OF SCREWS ON METAL CEILING STRUCTURES FOR DISMANTLING SYSTEMS

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ABSTRACT

In the dismantling works of office interiors for renewal, a robotic system is needed in order to assist the human workers engaged in this kind of job. Regarding to the items in the ceiling side, after a dismantling task of the ceiling boards, it is necessary to remove the screws that once held these boards to the Light Gauge Steel (LGS) with the purpose of reusing. At first, the paper presents the method to measure the 3D pose of the LGS. Thus the control system generates a trajectory under and near of that metal ceiling structure to measure the screws more precisely. The trajectory is followed for a robot arm which includes an eye-in-hand system. During the motion, the screws are detected by applying a template matching process to every single captured image. The detection of targets is tested under different lighting conditions and the effect of the number of images per meter is analyzed.

KEYWORDS

Dismantling System, Screw Detection, Pose Estimation of LGS

1. INTRODUCTION

Nowadays most works in the dismantling service are done by human manual operations, typically so-called "3K" works (kitsui, kitanai, kiken), that is, "tough", "dirty", and "dangerous". In addition, the number of workers will be decreasing drastically in Japan, so the construction industry will suffer serious shortage of labor power. Applying robotics technology is a requisite for solving the problem. Our short term goal is to develop collaboration between robots and human workers on disassembling ceiling materials including air conditioners and lighting appliances. Further details can be found in our work [1].

Regarding to the ceiling dismantling, first all appliances are removed carefully, then workers break and remove both ceiling panels and Light Gauge Steel (LGS) by using a simple tool, a long rod with sharp hook on its end.

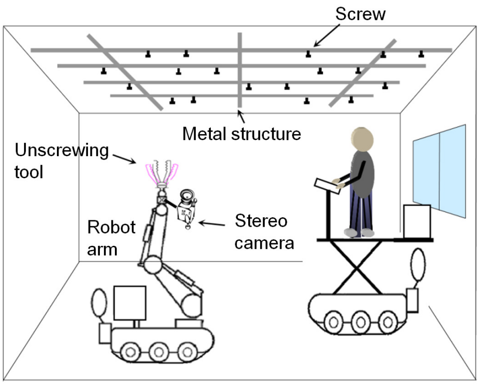

Figure 1. Concept for the screw removal task

In the renewal process using a robotic system, the LGS will be reused. A water jet cutter is being developed, that will be used to remove the ceiling panels without damaging the metal ceiling structure. Additionally, we need to remove the screws that once held the ceiling panels carefully without damaging the structure. Actually, there are around 30 per square meter of them and this task is one of the toughest since it has to be done repeatedly and against the influence of gravity. In our project, it is planned to engage elderly or physically challenged, and female workers in the dismantling service. Thus, we need to avoid the repetitive tasks for them.

With the robotic system, the human operator will do effortless work such as controlling the robot using an interface (See Fig. 1). One of our goals is to teach the robot arm to reach the targets easily. Additionally, the small size of the screws carries difficulties for their vision-based detection and the dismantling site is only illuminated by the day lighting.

Consequently, we propose a method for removing screws on metal ceiling structures. At first, the system measures the 3D pose of one of the linear structures of the LGS using the information of a stereo camera configured as eye-in-hand system. Thus, the control program will be able to define a trajectory for the robot near to the LGS to measure more precisely the screws attached to it. Furthermore, a lighting system attached on the robot will contribute to extract more characteristics of both the LGS and the screws. During the motion under the structure, the screws will be detected by applying a template matching algorithm to every single captured image. The results of all the processed images along the trajectory will be analyzed in order to measure both the true and the false positive detection rates in 2D space of the screws attached to the LGS.

In this paper, the objectives to be discussed are the robust 3D pose measurement of the LGS and the detection rate of the screws attached to that metal ceiling structure, both under different lighting conditions. Thus, Section 2 presents the proposed methodology to achieve the goals. Section 3 describes the related experiment and its results. The conclusion and future work are summarized in Section 4.

2. METHODOLOGY TO DETECT THE SCREWS

The screw detection task starts when the worker teleoperates the robot arm using an interface device. At first, the current detection of the LGS is shown in a monitor interface and once he considers that detection as a target, the control program estimates the pose of the LGS in 3D space. Thus, the program generates a trajectory for the robot near of the LGS to facilitate the screw detection process.

2.1. Pose Measurement of LGS

2.1.1. Detection of the LGS in 2D space

The control program detects one of the linear structures that belongs to the LGS. To achieve this phase, a line detection process applying the Hough transformation [2] to the input image is carried out. Then, the angle parameter of each detected line is analyzed using a voting process. In the voting space, the control program selects as initial interval that one with the largest amount of votes and that interval is increased considering the votes of its neighbors. The augmented interval contains the information of the largest amount of parallel lines in the scene.

The next target is to separate in groups the filtered lines, using now the position parameter in camera space of each line. First, by using both the angle average in the filtered group and the image's center, a new line is generated. The purpose is to create an extra line that can be able to cross every line in the filtered group, thus a perpendicular one is generated. Solving the related linear systems, the cross points are calculated and the grouping process is completed measuring the distance between the points. By using the information of the closest generated group to the image's center, the final linear segment is calculated.

2.1.2. Pose Estimation of LGS in 3D Space

With the selection in 2D space, the next step is the estimation of the physical position of that linear structure. The stereo camera measures the physical position of each point of the resultant line in camera space. Because lighting reflections in the metal frame, there are irregularities in the depth information. The 3D estimated points are then analyzed using the Principal Component Analysis (PCA), which performs an eigen-decomposition of the covariance matrix. Using $\boldsymbol{p}_i = (x_i, y_i, z_i)$; i = 1,2,…,s estimated points and being $\boldsymbol{q} = (\bar{x}, \bar{y}, \bar{z})$ the mean of the data, the covariance matrix can be computed as: $\mathbf{C}_{3x3} = \frac{1}{s}\sum_{i=1}^{s}(\boldsymbol{p}_i - \boldsymbol{q})(\boldsymbol{p}_i - \boldsymbol{q})^T$. From the covariance matrix, the three eigenvalues and the related eigenvectors can be calculated. The largest eigenvalue indicates where the data vary the most and in our case the direction of the related eigenvector ($\boldsymbol{v}$) is the orientation of the expected line. In order to complete the parametric equation of the line, the center of gravity of the raw data is used as a point that belongs to the line.

Including a shift to the generated line, the trajectory for the robot arm in the screw detection process is planned.

2.2. Screw Detection

Detection of bolts and nuts has been carried out in some previous works. In the inspection of railway infrastructure, a vision-based system detects the presence and the absence of the bolts on the sleepers in 2D space using artificial neural networks [3]. In [4] is presented an algorithm to detect the schematic representation of screws in mechanical engineering drawing, a line detection process is done in order to found the screw threads.

In our proposal to detect the screws, after the first approach by detecting the LGS, a template matching process is carried out. The threshold value to select candidates is not fixed, it depends of each image (see Fig. 2). Thus, at least 1 candidate is generated in every image.

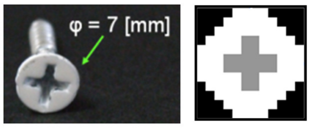

Figure 2. Left: a sample of the screws to be detected. Right: rough representation of the real screws using a grayscale template of 12x12[pixel] in size

2.2.1. Template Matching

During the motion of the robot arm along the generated trajectory, several images are captured using the eye-in-hand system. Every image is analyzed using the technique of template matching. The technique performs the normalized grayscale cross-correlation between a template and the image.

With the results of the LGS's pose, a fixed distance between the vision sensor and the ceiling structure can be set. Thereby, the template's size can be fixed considering the actual screw's diameter and the pinhole model of the camera. Three regions compose the template, the cross pattern, the circular region, and the background. The last one is set to zero, the circular one is white color, and the other one has a middle value.

2.2.2. Selection of Targets

After the template matching process in the k-th image, the control program selects candidates of the group $\mathrm{corr}_m; m = 1,2,...,(W-w)\times(H-h)$, where W and H represents the size of the source image, similarly w and h for the template, as follows:

$$\psi_m = \begin{cases} 1 & ; \; \textit{if } 0.99\max_k \le \mathrm{corr}_m \le \max_k \\ 0 & ; \; \textit{otherwise} \end{cases}, \tag{1}$$

in which $\max_k$ corresponds to the maximum correlation value in the image, $corr_m$ is the related correlation of the m-th point, and ψ_m equal to one means that point is a candidate. Under this approach, at least 1 candidate is generated.

Additionally, using the 3D pose information of the LGS, a limited area in 2D space can be generated considering the pinhole model of the camera, the current position of the robot arm, and the wide of the linear segment of the metal structure. Thus, the candidates outside of that area will not be considered.

3. EXPERIMENTAL RESULTS

An industrial robot PA-10 (Mitsubishi Heavy Industries, Ltd.) is used as a robot for the dismantling tasks and is teleoperated using a trackball interface device. The human operator controls the robot's motion with the purpose of locating a region of interest of the LGS in the camera's field of view. With the worker's judgment the starting position is given, thus the control system estimates the pose of the selected linear structure of the LGS and generates a trajectory for the robot. Along this trajectory, the screw detection task is carried out.

3.1. LGS Detection

To achieve the task, the control program gets images of the stereo vision sensor (Point Grey Research, Inc. BumbleBee2 camera with a resolution of 640x480 pixels RGB). With an eye-in-hand configuration, this sensor is attached to the robot arm in its tip. The camera is programmed for its maximum exposure value (2.41[EV]) and its minimal gain one (0.0[dB]). If these parameters are set in auto mode, the characteristics of the captured images change radically depending on the illumination conditions. For the camera calibration process, the extrinsic parameters are calculated by measuring the dimensions of the camera holder through design and by firmly fixing the camera to the robot. The intrinsic ones are calculated by a manual calibration process considering the perspective projection of the pinhole model.

With those conditions and through image processing, the control program detects the linear segments belonging to the metal ceiling structure. For a better estimation of 3D points in a stereo process, the final linear segment is selected as the closest one to the image's center. In Fig. 3 are

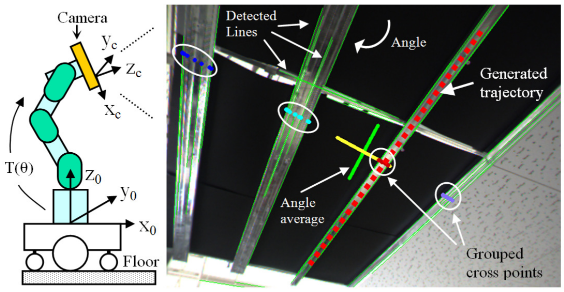

Figure 3. Results of the LGS detection in 2D space and coordinate frames. The background in black is to facilitate the comprehension of the results

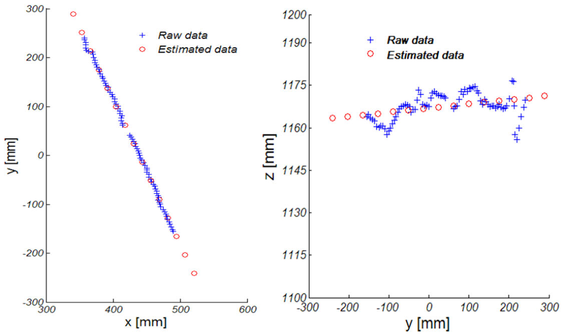

Figure 4. Results in the generation of the trajectory for the robot. The values are referred to the robot's base frame

depicted the results in 2D space applying the proposed method. Some of the image processes are achieved using the Open Source Computer Vision library (*OpenCV*) [5] from Intel Inc. Afterward, applying some functions of the Point Grey Triclops library [6], the stereo vision system calculates the physical position of each pixel contained in that linear segment, then the 3D raw data are referred to the robot's base frame. Considering every point, the covariance matrix is generated in order to apply the PCA. With $\boldsymbol{q}$ containing the mean of the data and being $\boldsymbol{v}$ the eigenvector corresponding to the largest eigenvalue of the covariance matrix, the control program generates a linear trajectory described as: $\boldsymbol{u} = \boldsymbol{q} + \lambda \boldsymbol{v}$. The interval for the scalar λ is calculated considering the robot's workspace boundaries. These results are depicted in Fig. 4.

Table 1. Angle error in the detection process of the linear structure considering lighting condition changes

Case	#[a]	Lab[b] [%]	Led[c]	Illumination [LUX] vsa[d]	window side 0[m]	window side 2[m]	‖Error‖ [deg] AVG	SD
A	25	0	ON	95	1170	170	1.9	0.7
B	20	50	ON	130	1120	167	2.4	1.6
C	10	100	OFF	260	1025	275	1.8	0.4

[a] Number of experiments.
[b] Number of fluorescent lamps turned on in our laboratory.
[c] Illumination system based in LED technology mounted on the robot.
[d] Vision sensor area.

In order to check both the accuracy and the robustness of the detection process, we measure the angle between the generated trajectory and the actual orientation of the selected linear structure. The last one is measured by an off-line positioning process of the simulated tool on the robot arm in 4 points of the LGS's geometry. For the evaluation, several experiments were done under different illumination conditions. In every condition, the experimental area was illuminated by the day lighting and was around 2[m] from the window side. Besides, the pose of the robot arm was set in a different location of its workspace. In the experiments presented herein, the initial position of the robot is around 1[m] from the LGS for every case, because robot's workspace limitations and a mobile base is not considered this time.

With the assumption that ceiling is parallel to floor and in our case the z_0 axis of the robot's base frame is perpendicular to both, the value of the z component of the eigenvector $\boldsymbol{v}$, described in Section 2, can be set to zero and consider only the orientation generated with the x and y components. Table 1 shows the results including this condition in its two last columns.

The A case in Table I has the same illumination conditions as in the real dismantling site. Considering the worst situation of this case, it means the 2.6 [deg] of error between the generated line and the actual one. For example, if the robot moves along the generated trajectory 1000[mm], the magnitude error to the actual trajectory at the end of the motion will be around 45[mm]. Also, it can be seen that the estimation of the LGS pose shows similar results at different lighting conditions.

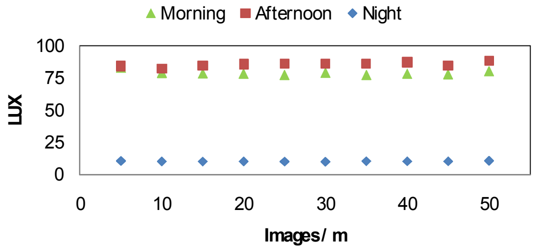

Figure 5. Lighting conditions for the screw detection tasks

Under the conditions of the A case of Table 1, the control program calculates the trajectory for the robot arm at 300[mm] under the metal ceiling structure. This facilitates the detection task of the screws attached to that structure.

3.2. Screw Detection

In the experiments presented herein, the number of real screws is 10 units and the number of images per meter is a parameter to be analyzed. Additionally, with the purpose of testing the system to lighting conditions changes, the experiments were carried out at different time of the day: morning, afternoon, and night. Near to the vision sensor, the intensity values of light of each situation as those mentioned above are shown in the chart included in Fig. 5.

3.2.1. Analysis of Template Matching

Every image along the robot's trajectory is analyzed in the 2D space using the correlation results of the template matching process. Several candidates are generated and only those ones completing the condition of Eq. 1 are considered in the process.

Fig. 6 depicts the correlation values at different lighting conditions. The values at night are the highest ones because only the LED light illuminates the targets and with the programmed parameters of the camera (exposure, gain) a dark background appears in the scene, examples of this situation are shown in Fig. 9. Nevertheless the correlation interval at different illumination conditions is acceptable for its steady and high value, in order to consider that area as a candidate.

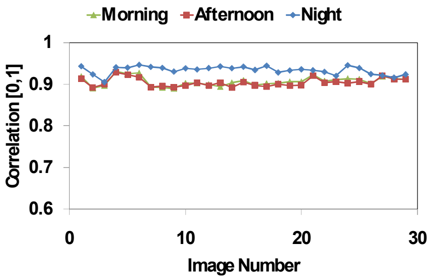

Figure 6. Correlation value at different illumination conditions. The system took 30 images along 1 [m]

3.2.2. Detection Rate of the Screws

In order to evaluate the detection rate of the screws in 2D space, the actual 3D position of each of the 10 screws is projected in camera space. The actual positions are measured by an off-line positioning process of the simulated tool of the robot arm in those screws and their projection is achieved considering both the pinhole model of the camera and the current position of the robot arm.

If the magnitude distance between a current candidate generated by the template matching process and one belonging to the projected group is within a neighborhood δ, then a screw is considered to be found and the True Positive (TP) rate is increased in one unit, 'hit'. If not, the False Positive (FP) rate is increased, 'false alarm'. The δ value was set experimentally to twice the screw's diameter in 2D space (24[pixel]). These rates are depicted in Fig. 7 considering the lighting conditions showed in Fig. 5 and different values in the number of images per meter [7, 8].

With reference to Fig. 7, while the number of images per meter increases, both the TP and FP rates increase too. The best performance of the detection is at night, where the FP rate is minimal because only the LED light illuminates the targets and a dark background appears in the images.

Regarding to the number of detections of each screw, Fig. 8 shows these results when the number of images per meter changes in a range from 10 to 50. The variations in the number of detections of each screw are caused by several reasons. For example, although in every case in Fig. 8, the lineal trajectory followed by the robot is the same, the illumination on the screws is different. Because sometimes, the lighting system mounted on the robot illuminates the LGS directly. This fact is produced by the limitation of 4 DOF of the robot arm which has a kinematics configuration of shovel machine. Consequently, the orientation of the end-effector is limited.

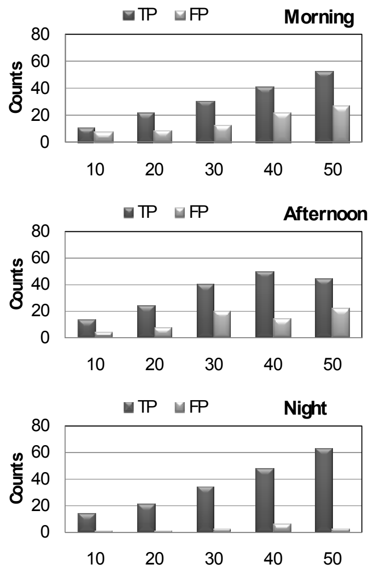

Figure 7. Detection rates considering the candidates under the condition of Eq. 1 and the limited area generated by projecting in 2D space the 3D pose of the detected region of the LGS. The horizontal axis corresponds to the number of images per meter

Another case is the low rate in the detection of the screw number 10; this is because that screw is located at the end of the robot's trajectory. But this drawback can be solved considering a mobile base.

On the other hand, about the parameter of images per meter, if this parameter is low the number of detections becomes also low, which in turn affects the possibility of successful screw detection. Conversely, if the number of images per meter becomes high, the number of detections of the screws increases too, but the time consumption to achieve the task becomes larger. Thereby, with the results depicted in Fig. 8, it is acceptable to work at 30 images per meter.

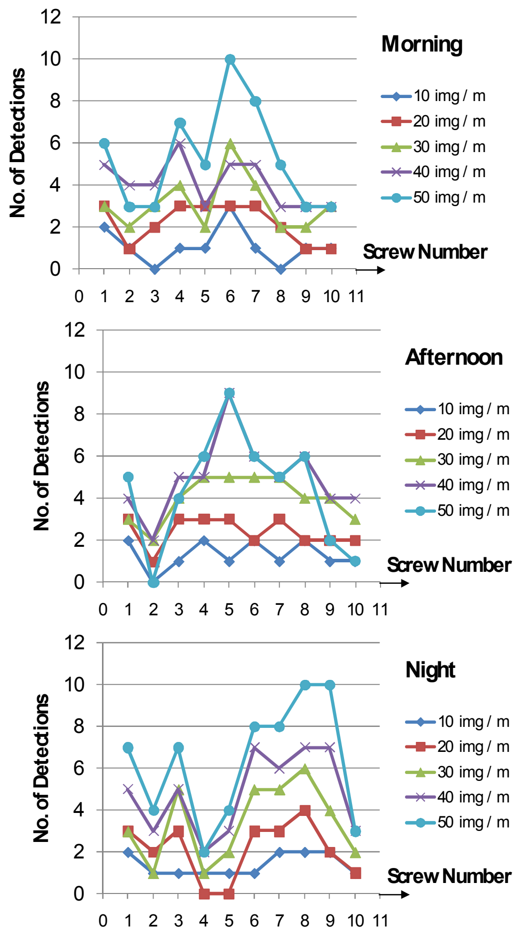

Figure 8. Individual detection in 2d space of the screws. The number of real screws is 10

4. CONCLUSION AND FUTURE WORK

The paper proposed a methodology where the human worker teaches the task to the robot easily. Only an initial position is required and the control system completes the next processes: the task of detecting screws on metal ceiling structures. The control program applies image processing functions to achieve the goals. At first, the LGS pose is measured in order to approach the robot arm to the targets. This measurement is robust, shows satisfactory results, and the generated trajectories will contribute to systematize the screw disassembling task. The screws on the ceiling structures are detected by applying the template matching process to every captured image along the robot's trajectory, where the number of images per meter was a parameter in the analyses. Additionally, the system was tested under different lighting conditions.

In our future work, the performance can be improved adjusting the camera parameters in order to get the images as in the night situation where the system has the best results. Also, estimating the 3D position of the detected screws will contribute to do a tracking process of them in 2D space. Thus, a multi-image integration could be achieved in order to increase the robustness of the detection. An example can be seen in Fig. 9, morning case. If the candidates detected in *image 22* could be projected in the *image 23*, the detection rate of the screws could be improved. Additionally, several templates will be made with different characteristics as background and intensity, in order to detect the screws for example when the LED lighting system illuminates directly the LGS.

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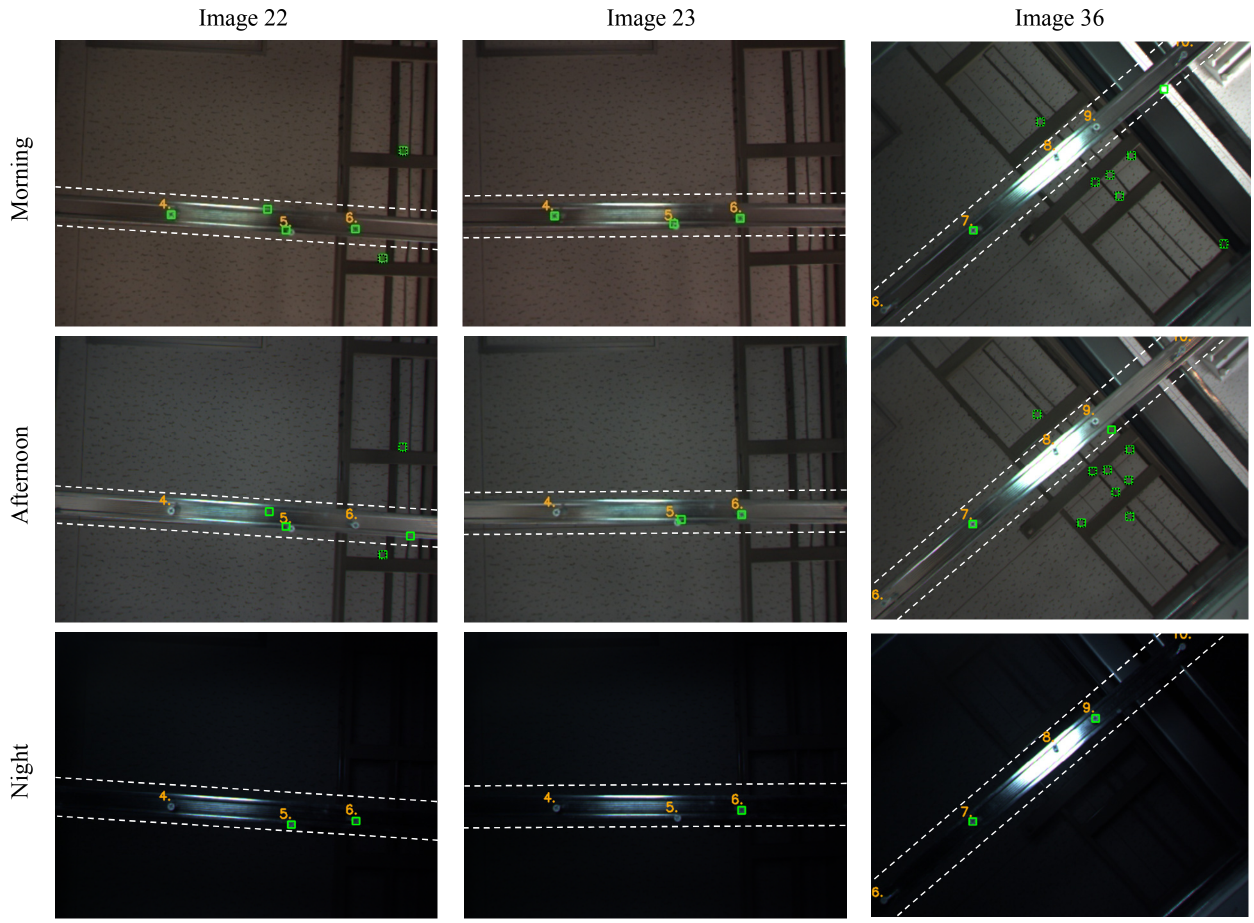

Figure 9. Examples of the detection of the targets in the images. The squared patterns are the best candidates generated by the template matching process. The squared patterns with solid line are considered in the analysis without those with dotted line outside of the limited area. This area encloses the detected ceiling structure. The numbers indicate a label to each real projected screw and the number of images per meter is 50 in this example

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