A Study on the Development of a Robot-Assisted Automatic Laser Hair Removal System

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Abstract

Background and Objective: The robot-assisted automatic laser hair removal (LHR) system is developed to automatically detect any arbitrary shape of the desired LHR treatment area and to provide uniform laser irradiation to the designated skin area. **Methods:** For uniform delivery of laser energy, a unit of a commercial LHR device, a laser distance sensor, and a high-resolution webcam are attached at the six axis industrial robot's end-effector, which can be easily controlled using a graphical user interface (GUI). During the treatment, the system provides real-time treatment progress as well as the total number of "pick and place" automatically. **Results:** During the test, it was demonstrated that the arbitrary shapes were detected, and that the laser was delivered uniformly. The localization error test and the area-per-spot test produced satisfactory outcome averages of 1.04 mm error and 38.22 mm²/spot, respectively. **Conclusions:** Results showed that the system successfully demonstrated accuracy and effectiveness. The proposed system is expected to become a promising device in LHR treatment.

Introduction

THE PRINCIPLE OF SELECTIVE PHOTOTHERMOLYSIS involves damaging hair follicles under laser light irradiation of the appropriate wavelength, pulse, and duration delivered without causing collateral damage to the surrounding tissue.^{1–4} A laser hair removal (LHR) practice that adopts this principle is economical, less painful to the patients, and time efficient compared with other hair removal practices, such as electrolysis/thermolysis, tweezing, or shaving.⁵ Moreover, various types of lasers used for LHR, including alexandrite, diode, Nd-YAG, ruby, and intense pulsed light (IPL), have all been approved by the United States Food and Drug Administration (FDA) and have all demonstrated effectiveness and safety when applied to LHR treatment.⁶ However, the LHR treatment has its drawbacks; for example, it is very difficult for the practitioner to trace the exact location of the laser irradiation spot by eye, because of the intrinsic characteristics of the laser, which only lasts from 3 to 400 ms.^{7–9} It takes longer to treat a wide coverage site, such as the back, leg, thighs, and hips, during which time the practitioner can lose focus. A group of

researchers proposed a thermovision camera to visualize the heat change in tissue to indirectly trace the laser irradiation.^{10–12} However, this is a less practical approach, because most of the LHR devices at the professional clinics have cooling tips built around the laser irradiation tip, which lessens the effect of thermovision camera.

Additionally, the innate nature of human error is a crucial factor that determines the overall performance of the successful treatment. The practitioner may mistakenly not treat of a site or overexpose one of the patient's treatment sites,⁶ particularly under the fatigue associated with the prolonged treatment process. Hair on the overlooked area will continue to have normal hair growth activity, which leads to a sub-optimal outcome. Therefore, an adequate amount of fluence and a uniform distribution of laser treatment are crucial for the safety of the patient and the efficacy of the hair removal treatment.¹³ Ineffective laser treatment can lead to side effects in the skin, such as pigment alteration, blistering, and erythema.^{14,15} To avoid omitting or overexposing laser treatment sites, uniformity of the laser emission and the tracking of the laser emission is required.¹²

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FIG. 1. Operation order of the proposed system.

The present study is focused on achieving a safe and effective LHR system using uniform laser irradiation. It is a visually guided, robot-assisted LHR system that automatically detects the target and performs the “pick and place” motion. A red-colored subject is employed as a target to

evaluate the performance of the system, and a clinical trial involving human subjects is planned as a future study.

Methods

Experimental devices

The proposed system uses the “pick and place” technique, because of its flexibility in application, as well as confirmation of the laser-irradiated spot and the spot to be irradiated. It is assumed that the region of interest (ROI) for the LHR target is a smoothly contoured surface area, in which no rapid rise or fall exists. The difference in height from one spot to another is assumed to be small during the target’s planar movement involved in the robot’s “pick and place” movement, and the workspace area is $<200 \times 400 \text{ mm}^2$. The camera (LifeCam Studio, Microsoft, CA) attached onto the end effector automatically detects any arbitrarily shaped and sized target in red. Then, the robot executes the “pick and place” motion on the target’s entire area. Figure 1 shows the brief operation order of the proposed system. The laser is irradiated only when its laser output window (LOW) is in contact with the skin, for maximal efficacy and safety.

Figure 2 shows the hybrid control scheme for integrating the vision and laser sensor on a robot. Once the robot task is implemented by the system, the vision system and laser sensor receive the data from the external environment. The hybrid robot position controller integrates the procedures and commands each joint controller to determine the relevant task frame poses and the velocity of each joint. The overall components and software are listed in the Tables 1 and 2, and the proposed system’s exterior appearance is shown in Fig. 3.

Figure 4a shows the coordinates of the objects relative to the camera coordinate frame. The coordinates C^x and C^y form the image plane, which is parallel to the horizontal axis of the image while aligned with the optical axis of the lens. The robot’s end effector coordinates are denoted as R^x , R^y , R^z , which represent the Cartesian coordinates x , y , and z , respectively. The end effector is the device at the end of the robot arm. In this article, a unit composed of LHR device, camera, tactile sensors, and laser distance sensor is considered to be the end effector. Figure 4b shows the simplified application of the proposed system operating on a human back. The position of the six axis robot arm end effector is expressed in

FIG. 2. Hybrid control scheme for integrating vision and laser sensor on a robot.

TABLE 1. SUMMARY OF THE DEVICE SPECIFICATIONS

<i>Device</i>	<i>Model, manufacturer</i>	<i>Size (width × length × height)</i>	<i>Specification</i>
LHR device	Tria Plus TM , Tria Beauty [®]	80 × 120 × 220 mm ³ (~)	Fluence: 11–26 J/cm ² Pulse duration: 100–350 msec Output wavelength: 810 nm Laser type: Diode laser Laser class: 1
Laser distance sensor	optoNCDT 1302 TM , Micro-Epsilon [®]	20 × 80 × 65 mm ³	Measuring ranges: 20–200 mm Resolution max: 4 μm
Camera	LifeCam Studio TM , Microsoft [®]	40 × 113 × 50 mm ³	Autofocus: 0.1–10 m, Resolution: 1920 × 1080 p HD Frames/sec: < 30 Automatic image adjustment CMOS sensor technology
Six axis robot	VS-6556G TM , Denso Robotics [®]	578 × 578 × 578 mm ³ (~)	Max payload: 7 kg Max reach: 650 mm
Computer	Self-assembled	30 × 30 × 20 mm ³ (~)	Intel i7 TM , 12 GB RAM
Sensor controller	Uno R3 TM , Arduino [®]	53 × 75 × 13 mm ³	ATmega328 MCU Input voltage: 7–12 V 14 Digital I/O pins 32k Flash memory
Tactile sensors	ITS-1109, YungSung Elec.	6 × 6 × 4 mm ³	Rating: DC12V, 50 mA Travel: 0.2 ± 0.1 mm
Red paper target	Red, Jongienara	Arbitrary shape	Red colored paper

LHR, laser hair removal; CMOS, complementary metal-oxide semiconductor.

terms of the reference frame, which is the robot base, denoted as O^x , O^y , O^z . Overall, the position of the end effector camera and laser sensor are fixed, installed as shown in Fig. 4a, and both remain perpendicular to the base ground.

The laser distance sensor is attached onto the end effector, as shown in Fig. 3. By using the one-dimensional laser distance sensor, the distance between the sensor and the object can be received. The laser sensor continuously projects a laser-generated red dot on the object's surface for visual location. Also, a z-coordinate value for robot can be easily obtained, because the end effector is controlled to be parallel to the base ground throughout the procedure.

Image processing and work planning

In the present study, the target area to practice the “pick and place” motion is designated by red colored paper of arbitrary shape. The following describes the process how an

object is recognized to be the target and how the coordinates are assigned.

Color segmentation and center coordinates detection. Once the system receives the raw image from the camera, the system undergoes color segmentation. The red-green-blue (RGB) color segmentation is used to isolate the object of a specified color range in an RGB image.¹⁶ Using this method, any color of pixels other than red are discarded, leaving only the red pixel > 190. To detect the center of the arbitrary target, the concept of the geometric centroid is adopted. The coordinates of the centroid are

$$\bar{x} = \frac{1}{A} \sum_{i=0}^N x_i \Delta A, \quad \bar{y} = \frac{1}{A} \sum_{i=0}^N y_i \Delta A \quad (1)$$

where A is denoted for the area of the arbitrary target. The coordinates $\bar{x}$ and $\bar{y}$ represent the center coordinate of the target, and the robot will move to this coordinate and maintain a distance of 250 mm from the target by utilizing the laser distance sensor. The center of the camera's image frame is matched with target's center coordinate.

Edge detection. Canny edge algorithm¹⁷ assembles the individual edge candidate pixels to contours so that two thresholds, an upper and a lower one, are formed. Only the edges within two threshold values are accepted.¹⁸ The present system used eight bit gray scale binary threshold, in which any pixel values > 90 are converted to 255 (white), and values < 90 are converted to zero (black).

Work planning. The virtual gridlines are generated on the image, using both horizontal and vertical lines, such that

TABLE 2. SUMMARY OF THE SOFTWARE SPECIFICATIONS

<i>Software</i>	<i>Manufacturer</i>	<i>Other</i>
Visual Studio MFC 2010 TM	Microsoft [®]	Operation Integrated Development Environment (IDE)
MEDAQLib V3.2.1	Micro-Epsilon [®]	Laser distance sensor control program
OpenCV 2.4.2	Intel [®]	Vision and image processing library
Arduino 1.0 IDE	Arduino [®]	Arduino signal processing control program

FIG. 3. The proposed system's hardware.

each grid's center coordinates are 6 mm apart from its neighboring grids. A distance of 6 mm is recommended by the LHR device manufacturer's manual. Using the gridlines, we determined the designated locations for the assigned "pick and place" coordinates of the arbitrarily shaped target.

After the each of the desired coordinates for "pick and place" is extracted, the robot's end effector moves toward each location of the target. While the camera's visual data are used to collect the planar location, the laser distance sensor is used to calculate depth. The laser sensor, which is fixed at the end effector, measures the precise distance between the target and the laser sensor, and then the data are

used for robot control, to enable contact with the target. The basic mechanism involves mapping (coordinate transformation) the extracted camera coordinates to the robot's coordinates. The following equations (2 and 3) and Fig. 5 describe the method for mapping, and Equation 4 is used to maintain the 250 mm vertical distance from the object.

$$R_x = \frac{R_3^x - R_1^x}{C_3^y - C_1^y} C_y + R_1^x - \frac{R_3^x - R_1^x}{C_3^y - C_1^y} C_1^y \quad (2)$$

$$R_y = \frac{R_2^y - R_1^y}{C_2^x - C_1^x} C_x + R_1^y - \frac{R_2^y - R_1^y}{C_2^x - C_1^x} C_1^x \quad (3)$$

Where R_x and R_y , are the end effector's x and y coordinates, respectively, and C_x and C_y are the camera's x and y coordinates, respectively. R_n^x and R_n^y are the end effector's coordinate values extracted from corresponding camera coordinates C_n^x and C_n^y . The camera coordinate values are measured in whole numbers, whereas those of the robot are returned with a precision to the hundredths decimal place. Figure 5a depicts the coordinate data of x and y received from the camera.

$$Z_d = Z_{Cur} - (Z_l - Z_r) \quad (4)$$

where Z_d , Z_{Cur} , Z_l , and Z_r are the desired z coordinate of end effector, the current z coordinate of the end effector, the measured value from the laser sensor, and the reference distance (which is 250), respectively.

Verification

Localization error test. The localization error test used to validate the accuracy and precision of the automated proposed system is assessed by comparing the detected target's

FIG. 4. (a) Robot base coordinate, end effector coordinate, and camera coordinate. (b) Virtual patient in treatment. (c) Laser hair removal (LHR) practice progress shown in terms of completion rate. Black filled area signify completion. The laser output window (LOW) contact starts from the top left and ends at the bottom right. From top to bottom, 0%, 30% (4 min 09 sec elapsed), 60% (8 min 19 sec elapsed), and 100% (14 min 7 sec elapsed) respectively. The robot moved with uniform acceleration and deceleration—both took 4.41 m/sec^2 . The area of target is $90 \times 90 \text{ mm}^2$, and the total number of "pick and place" spots is 210.

FIG. 5. Coordinate mapping example. (a) Coordinates received from the vision sensor. (b) Parameters of each coordinate used for mapping.

position with the reference coordinates of the robot. The graph paper is precisely positioned in accordance with the robot's reference coordinate point, p_{ref}^{tgt} , which serves as a reference to be measured. The dimension of the test area is set to $400 \times 200 \text{ mm}^2$, which is sufficient to cover a human back; the 15 points with an equal distance of 100 mm from each neighboring point are depicted in Fig. 6. A $6 \times 6 \text{ mm}^2$ square red colored paper target is placed on points ranging from P_{11} to P_{35} . The target's position is well placed on the graph paper to minimize the displacement error by carefully matching its center with the reference point. Be-

cause the laser distance sensor is fixed on the robot's end effector, the laser beam is always pointing perpendicular to the ground, which serves as a visual locator to provide an accurate result. The proposed test is to simply detect the $6 \times 6 \text{ mm}^2$ red colored paper target and to move to the target from the initial position so that the laser distance sensor's laser beam is reflected on the target. Because the robot's encoder provides the Cartesian coordinate values of the end effector's position, it is utilized to test the localization capability of the proposed system. A round of the test set consisted of moving P_{11} to P_{35} without staying more than

FIG. 6. Localization test board on graph paper. Total dimensions in $200 \times 400 \text{ mm}^2$, each point neighboring another by 100 mm. Each point was given in P_{CR} where $C = (1,2,3)$ and $R = (1,2,3,4,5)$.

FIG. 7. Various types of arbitrary shaped target detection results. From **a** to **d**, area per spot was measured 38.04, 38.63, 38.02, and 38.20 mm²/spot, respectively.

once per position, which is manually moved from each point, and 10 rounds of the test are performed to provide 150 samples of data.

For each center of the image data set from the target, P_{img}^{tgt} , is calculated as the center of target. The transformation matrix for relating the image to the robot end effector's Cartesian coordinates, T_{img}^{real} , is determined by the pair-point matching method, which is implemented using Equations 3 and 4. Therefore, the localization error is

$$Localization\ Error = |P_{ref}^{tgt} - T_{img}^{real} \cdot P_{img}^{tgt}| \quad (5)$$

Area-per-spot test. The area-per-spot test is performed to verify the effective and consistent detection capability of the proposed system. Under the assumption that a uniform distribution of laser irradiation is achieved within the target, this result value can be used to measure the quantitative

FIG. 8. Graphic user interface (GUI) panel. Filled out black regions show irradiated treatment and yellow hollow circles are to-be-irradiated zones.

TABLE 3. LOCALIZATION ERROR RESULTS

	<i>Mean (mm)</i>	<i>SD</i>
P ₁₁	1.76	0
P ₁₂	1.74	0.30
P ₁₃	1.34	0
P ₁₄	0.45	0
P ₁₅	0.75	0
P ₂₁	1.33	0
P ₂₂	1.79	0
P ₂₃	0.44	0
P ₂₄	0.66	0
P ₂₅	1.25	0
P ₃₁	1.02	0
P ₃₂	0.40	0
P ₃₃	1.29	0
P ₃₄	0.48	0
P ₃₅	0.99	0

omittance or overlap rate. The spots are the locations within the target area where the laser irradiation treatment is to be implemented, whereas the area is the target's size within the image frame. Once the target is set, the system can automatically count and identify the exact locations for laser irradiation. Different sizes of squares, right triangles, and circles were selected and tested for five rounds, with a total of 90 samples collected. For each figure, a round set consisted of detecting the smallest to largest size in a consecutive manner, and with no one figure being tested more than once per trial. Five set of rounds were tested. Arbitrarily shaped figures were also tested by measuring their approximate areas. The figures were manually drawn on graph paper with nonreflective red marker. The area approximation is measured in terms of a 5×5 mm² grid. The area that completely fills 25 mm² in red is considered 25 mm², whereas any uncompleted area in red is considered half of the completed area, which is 12.5 mm². The total area constitutes the sum of those areas. Four samples were used in the trial.

Results

The target detection result of various arbitrary shapes is shown in Fig. 7, and the GUI panel, which presents the sequence of operation, is shown in Fig. 8. Filled out black regions are completed irradiated zones, whereas yellow hollow circles are the to-be-irradiated zones. The “pick and

place” movement used to implement the laser treatment starts from top left to right, and then moves to the next row. The “operation steps” group, located at the bottom left, provides all the data that are required for controlling the robot. On screen, “Tria displacement” is the distance between one center of a circle and another. “Total No. of Pick and Place” is computed and displayed as soon as the “Practice” button is activated. The completion progress bar and percentage are displayed in real time. Once the last spot is completed, the robot's end effector moves to the initial position.

Localization error test

One hundred and fifty samples were collected successfully, and the laser beam from the distance sensor was identified near each target's center point. The distance between the laser distance sensor and the target was maintained at 250 mm. Table 3 depicts the test result of 10 rounds of 15 different points. The lowest error was taken from P₃₂ (mean error: 0.40 mm) and the highest error was from P₂₂ (mean error: 1.79). The time required for the entire procedure per trial was typically <40 sec, whereas it took <1 sec to detect the target from the initial position, and the coordinate value of the center point of the target was identified in real time on the GUI panel. The rest of the time spent was attributed to the robot's movement and the clicking operation buttons on the GUI panel.

Area-per-spot test

Various shapes and sizes of ideal form figures, including squares, right triangles and circles, had averages of 37.89 cm²/spots (SD: 2.67, *n*=40), 38.03 cm²/spots (SD: 2.10, *n*=30) and 38.21 cm²/spots (SD: 0.65, *n*=20), respectively (Table 4). The results for the arbitrarily shaped figures from Fig. 7 are also presented on Table 5. The speed of the robot movement is manually adjustable. By fixing its acceleration and deceleration at 4.41 m/sec², it took <3 sec to move from one spot to another.

Discussion

The localization error test results indicated success with regard to accuracy and precision, considering that the vision sensor used is an off-the-shelf HD webcam. The tendency toward a high number of errors on the edge points among

TABLE 4. AREA-PER-SPOT TEST FOR SQUARES, RIGHT TRIANGLES, AND CIRCLES

<i>Square (mm²)</i>	<i>Area/spot (mm²/spot)</i>	<i>Right triangle (mm²)</i>	<i>Area/spot (mm²/spot)</i>	<i>Circle (radius) (mm)</i>	<i>Area/spot (mm²/spot)</i>
30×30	36.00	50×50	34.72	20	38.07
40×40	44.44	60×60	40.00	30	37.20
50×50	39.06	70×70	37.12	40	38.66
60×60	36.00	80×80	41.02	50	38.81
70×70	37.12	90×90	38.57		
80×80	37.86	100×100	36.76		
90×90	36.00				
100×100	36.63				
Average	37.89	Average	38.03	Average	38.21
SD	2.67	SD	2.10	SD	0.65

TABLE 5. AREA-PER-SPOT TEST FOR THE ARBITRARY SHAPES IN FIG. 7

Arbitrary shaped figures	Area measured in approximation (mm ²)	Area/spots (mm ² /spots)
Fig. 7a	3500	38.04
Fig. 7b	1687.5	38.35
Fig. 7c	3650	38.02
Fig. 7d	3425	38.48
Average	N.A.	38.22
SD	N.A.	0.19

the 15 points may be attributed to the fish-eye effect, which is the distortion of the image caused by the curvature of the lens. More specifically, the fish-eye effect occurs because the incoming light from the farther edges are more bent than the one from the center. Therefore, as it gets farther from the center, the image gets more distorted. To alleviate the fish-eye effect, a chess board calibration will be added in the near future. This image processing method can obtain images of which the edge distortion is highly reduced by presenting a black-and-white chessboard image to the camera.¹⁹ However, among the factors that contributed to the error, it is suspected that laser beam size (circle, $d=2$ mm) is the most significant. The laser beam provided visual guidance for calibrating the pair-point matching method. Serious efforts were made during the calibration to take precise measurements, but it would be much more effective to adopt a laser beam pointer with a smaller diameter, which would provide a finer measurement by reducing the localization error. The low standard deviation values of each point are the result of camera coordinate values that are extracted in terms of whole numbers, whereas the robot's coordinate values are given to hundredths of a decimal place. The relatively high standard deviation on P_{12} might be the result of the test environment; for example, a ceiling light directly above the point where the light was reflected most could result in oscillation in the detection of the target's center point.

The area-per-spot test results for detection capability were consistent in both ideally formed and arbitrarily shaped figures. Given a radius of 5.5 mm, the LOW area for Tria Plus is 95.03 mm². The experimental result presented in the various figures measured using the proposed system is ~ 38 mm²/spots, which is ~ 2.5 times as much as the difference. Adopting this system to other LHR devices with a square-shaped LOW would increase the ratio.

The current system leaves some undetected areas along the edges, because they lack sufficient color regions to be considered an irradiation site. The image processing algorithm creates the lattices on the detected target, which has $>60\%$ of its contents. Because the proposed system is primarily aimed at treating a wide coverage area, where sensitive regions are not included, the user may employ manual treatment along the edge line.

Conclusions

The system operates well regardless of the clinical environment and skill of the user. The simplicity and accuracy of the proposed system can be applied to various types of laser surgeries for cosmetic and dermatologic treatments,

especially when a controlled dosage of laser irradiation is desired.

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References

- Anderson, R., and Parrish, J. (1983). Selective photothermolysis: precise microsurgery by selective absorption of pulsed radiation. *Science* 220, 524–527.
- Adrian, R.M. (1999). Pulsed carbon dioxide and long pulse 10-ms erbium-YAG laser resurfacing: a comparative clinical and histologic study. *J. Cosmet. Laser Ther.* 1, 197–202.
- Kushikata, N., Negishi, K., Tezuka, Y., Takeuchi, K., and Wakamatsu, S. (2005). Non-ablative skin tightening with radiofrequency in Asian skin. *Lasers Surg. Med.* 36, 92–97.
- Fitzpatrick, R.E., Rostan, E.F., and Marchell, N. (2000). Collagen tightening induced by carbon dioxide laser versus erbium:YAG laser. *Lasers Surg. Med.* 27, 395–403.
- Lepselter, J., and Elman, M. (2004). Biological and clinical aspects in laser hair removal. *J. Dermatolog. Treat.* 15, 72–83.
- Ibrahimi, O.A., Avram, M.M., Hanke, C.W., Kilmer, S.L., and Anderson, R.R. (2011). Laser hair removal. *Dermatol. Ther.* 24, 94–107.
- Dierickx, C.C., Grossman, M.C., Farinelli, W.A., and Anderson, R. (1998). Permanent hair removal by normal-mode ruby laser. *Arch. Dermatol.* 134, 837–842.
- Nanni, C.A., and Alster, T.S. (1999). Laser-assisted hair removal: side effects of Q-switched Nd:YAG, long-pulsed ruby, and alexandrite lasers. *J. Am. Acad. Dermatol.* 41, 165–171.
- Nanni, C.A., and Alster, T.S. (1999b). Long-pulsed alexandrite laser-assisted hair removal at 5, 10, and 20 millisecond pulse durations. *Lasers Surg. Med.* 24, 332–337.
- Dąbrowski, M., Dulski, R., Żmuda, S., Zaborowski, P., and Pogorzelski, C. (2002). The use of thermovision camera to observe physiological and pathological conditions of oral cavity mucous membrane. *Infrared Phys. Technol.* 43, 265–269.
- Marchesini, R., Andreola, S., Emanuelli, H., Melloni, E., Schioli, A., Spinelli, P., et al. (1985). Temperature rise in biological tissue during Nd:YAG laser irradiation. *Lasers Surg. Med.* 5, 75–82.
- Koprowski, R., Wilczynski, S., Samojedny, A., Wrobel, Z., and Deda A. (2013). Image analysis and processing methods in verifying the correctness of performing low-invasive esthetic medical procedures. *Biomed. Eng. Online* 12, 51.
- Alexiades-Armenakas, M.R., Dover, J.S., and Arndt, K.A. (2008). The spectrum of laser skin resurfacing: Non-ablative, fractional, and ablative laser resurfacing. *J. Am. Acad. Dermatol.* 58, 719–737.
- Lim, S.P.R., and Lanigan, S.W. (2006). A review of the adverse effects of laser hair removal. *Lasers Med. Sci.* 21, 121–125.
- Lanigan, S.W. (2003). Incidence of side effects after laser hair removal. *J. Am. Acad. Dermatol.* 49, 882–886.
- Gonzalez, R.C.W.R. (2008). Digital image processing. Upper Saddle River, NJ: Prentice Hall.

17. Canny, J. (1986). A computational approach to edge detection. *IEEE Trans. Pattern Anal. Mach. Intell.* 8, 679–698.
18. Bradski, D.G.R., and Kaehler, A. (2008). *Learning OpenCV*. Sebastopol, CA: O'Reilly Media, Inc.
19. De la Escalera, A., and Armingol, J.M. (2010). Automatic chessboard detection for intrinsic and extrinsic camera parameter calibration. *Sensors* 10, 2027–2044.

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