Positioning and Aiming Algorithm of Target in the 3D Space

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Abstract: Target’s positioning and aiming is one of the most significant function for robotic system in high-risk environment, especially for the anti-terror work robot. A novel target positioning and aiming method was proposed in this paper. The method had achieved target’s positioning and aiming by positioning unit and aiming unit, separately, which are in the environment that people can’t reach. The positioning unit is formed by laser rangefinder(LR), 2-D pan/tilt and CCD camera; the aiming unit is formed by 2-D pan/tilt and firearm. The coordinate system of the model was built by using the D-H coordinate system defined method; the target position within the basic coordinate system on the aiming unit can be obtained through the positioning algorithm by using Transform Matrix(TM) and the distance of the LR on the positioning unit, which as the input of the aiming unit, using the inverse kinematics model of the aiming unit, then the target can be aimed by the firearm through controlling the steering engines on the aiming unit. Despite the existence of error, however, the test analysis showed that the effectiveness of this method is verified, and guarantees a certain degree of real-time performance and operability. It also has some promotion significance in engineering.

1. Introduction
With the development and widespread use of tele-operated robotic systems in high-risk environment, positioning and aiming have become fundamental issues that must be addressed in order to provide autonomous capabilities to a robot, especially, such as target positioning of the anti-terrorism robot, precision guidance and avoiding obstacle of the robot, etc [1-4]. Target positioning is a technique to obtain the three-dimensional coordinate of a non-contact object or point, which is the pre-condition of aiming system; Target aiming is a system that makes the firearms aim the object. target positioning and aiming are important part of systems’ engineering capabilities and operational efficiency in the place that people can’t reach.

Successfully exploited alternative techniques have been reported such as structured light, infrared radiation, radio frequency and vision[5]. Many similar measurements system are developed, such as position measurement by 2-D laser scanner [6], the positioning target so much like a cylinder, it has strong dependence on environment; A novel target positioning system based on a laser rangefinder (LR) and Micro Electro Mechanical Systems (MEMS) gyros was proposed by Cheng et al [7], MEMS gyros are used to derive the attitude of LR, and the LR is applied to measure the distance between the observer and the target; An accurate and fault-tolerant target positioning system for buildings using Laser Rangefinders(LRs) and Low-Cost MEMS-Based MARG Sensors was proposed by Zhao et al[8], both accelerometer/magnetometer and LR attitude aiding systems are introduced to aid MEMS gyros; Vision sensors(e.g., cameras) can
provide accurate target position information, but the corresponding camera modeling and image processing algorithms are complex and time-consuming, position measurement by vision and laser [9-14], it needs to put a special mark on target, the mark helps to identify the target, or need to modeling of target objects in advance; Infrared Radiation(IR) sensors and Radio Frequency(RF) localization system are available options for positioning the target. However, IR signals are limited to the available line of sight [15-17]. RF systems are imprecise in positioning targets [18]. Through the above-mentioned review, most researchers focus on the target positioning. As we know, target positioning is the precondition of aiming target, Therefore, in order to achieve this purpose, a novel target positioning and aiming system and method was proposed in this paper. The complete process of synthesis, analysis, implementation, and validation is presented next.

This article is organized as follows: the mechanical structure and the main methodologies used in the positioning and aiming system proposed are described in section 2; the D-H coordinate system of the model and algorithms of positioning and aiming are studies in detail in section 3; analyzes the experimental results obtained in section 4 and some concluding remarks are addressed in section 5.

2. System Structure’s Fundamental

Mechanical structure of the proposed target positioning and aiming system was shown in Fig.1. Included two parts, A: Positioning unit and B: Aiming unit. It consists of operating detection camera; laser rangefinder; horizontal and pitch structure; steering engines and firearm. The involved algorithms include two parts, target positioning and aiming algorithm. The overall structure of the system was shown in Fig.2.

2.1. Positioning Process

Firstly, the LR sensor point to the target object through controlling the two steering engines on the positioning unit. Secondly, the distance between the sensor and the target was obtained. The last but not least, the target position within the basic coordinate system on the aiming unit was computed by the distance and the coordinate system transformation matrix.

2.2 Aiming Process

First of all, the inverse kinematics model of the aiming unit was built. Next, the joint angles of the steering engines on the aiming unit were computed through the target position and the model. Finally, the steering engines were controlled to rotate the above-mentioned joint angles from the initial state, then the firearm can aim the target.
3. Target Positioning and Aiming Algorithms

The underlying idea of target positioning is presented as follows. First, the relation between Laser Range Finder and a target and the relation between Laser Range Finder and the basic coordinate system are built. Second, provided the Laser Range Finder position within the basic coordinate system, then the target position can be computed with the built relation. Third, if required, the target position in an arbitrary coordinate system can be obtained when knowing the Transform Matrix(TM) from the original coordinate system to this arbitrary co-ordinate system. The principle of the target positioning is shown in Fig.3.

3.1 Build the Coordinate Systems

According to the above mentioned target positioning algorithm and the mechanical structure, The \( \mathcal{O}_0\)-\(X\hat{y}_0\hat{Z}_0\), \( \mathcal{O}_1\)-\(X\hat{y}_1\hat{Z}_1\), \( \mathcal{O}_2\)-\(X\hat{y}_2\hat{Z}_2\) and \( \mathcal{O}_3\)-\(X\hat{y}_3\hat{Z}_3\) coordinate systems are built on the Positioning unit by the D-H coordinate system defined method, respectively, Hereinafter referred to as \( \mathcal{O}_0\), \( \mathcal{O}_1\), \( \mathcal{O}_2\) and \( \mathcal{O}_3\) coordinate system. The \( \mathcal{O}_0\) coordinate system where in the center of the bottom of the laser positioning unit, is the basic coordinate system; The \( \mathcal{O}_1\) coordinate system which is in the center of the horizontal rotation joints axis, bindings in the coordinate system of the horizontal rotating joints and does horizontal rotation with the coordinate system of the horizontal rotating joints, the \( \vartheta_1\) denote the horizontal rotational angle. The \( \mathcal{O}_2\) coordinate system which is in the center of the pitching rotation joints axis, bindings in the coordinate system of the pitching rotating joints and not only does horizontal rotation with the coordinate system of the horizontal rotating joints but also does pitching rotation with the coordinate system of the pitching rotating joints, the \( \vartheta_2\) denote the pitching rotational angle, its origin is the same to the origin of the \( \mathcal{O}_1\) coordinate system. The \( \mathcal{O}_3\) coordinate system which is on the certain height in the \( \hat{Z}_2\) axis direction of the \( \mathcal{O}_2\) coordinate system, bindings in the laser range sensor, maintains translational relations with the \( \mathcal{O}_2\) coordinate system and therefore their motions are the same. the laser beam direction is the same to the \( \hat{X}_3\) axis direction. In the same way, the \( \mathcal{O}_{1,}\)-\(X\hat{y}_1\hat{Z}_1\), \( \mathcal{O}_{2,}\)-\(X\hat{y}_2\hat{Z}_2\) and \( \mathcal{O}_{3,}\)-\(X\hat{y}_3\hat{Z}_3\) coordinate systems are built on the Aiming unit. \( \beta_1\) and \( \beta_2\) are used to denote the angles of horizontal and pitching rotation, respectively. The schematic diagram of the coordinate system is shown in Fig.4.
3.2 Target Positioning Algorithm

In accordance to the transform relationship between adjacent coordinate system on the Positioning Pan/tilt, we supposed that $A_{0'}^0$ denotes the TM from $O_0'$ to $O_0$; $A_0^1$ denotes the TM from $O_0$ to $O_1$; $A_1^2$ denotes the TM from $O_1$ to $O_2$; $A_2^3$ denotes the TM from $O_2$ to $O_3$; $P = (d, 0, 0, 1)^T$ denotes the target position in $O_3$; $d$ denotes the distance between the target and LR; then the target position within the $O_0'$ coordinate system $P'$ can be expressed as:

$$P' = A_{0'}^0 \cdot A_0^1 \cdot A_1^2 \cdot A_2^3 \cdot P$$

where, $A_{0'}^0$, $A_0^1$, $A_1^2$ and $A_2^3$ are given by:

$$A_{0'}^0 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad A_0^1 = \begin{bmatrix} \cos \theta_0 & -\sin \theta_0 & 0 \\ \sin \theta_0 & \cos \theta_0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad A_1^2 = \begin{bmatrix} \cos \theta_2 & 0 & \sin \theta_2 \\ 0 & 1 & 0 \\ -\sin \theta_2 & 0 & \cos \theta_2 \end{bmatrix}, \quad A_2^3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

By substituting $P$, $A_{0'}^0$, $A_0^1$, $A_1^2$ and $A_2^3$ into Eq. (1), the $P'$ is calculated by the following expression:
\[ 0^P T = [x_0, y_0, z_0]^T \]
\[ = [d \cos(\theta) \cos(\theta_2)] \]
\[ P_y + P_z \sin(\theta) \sin(\theta_2) + d \sin(\theta) \cos(\theta_2) \]
\[ P_{z1} + P_z \cos(\theta_2) - d \sin(\theta_2) \]
\[ 1 \]
\[ (2) \]

where \( P_y, P_z \) and \( P_{z2} \) are constants of model parameters; \( \theta \) and \( \theta_2 \) are obtained from the servo encoder feedback of the steering engines; \( d \) is obtained from LR. Hence, the target position \({}^0P^r\) can be calculated.

3.3 Target Aiming Algorithm

In accordance to the transform relationship between adjacent coordinate systems on the Aiming Pan/tilt. If the steering engines of the horizontal and pitching rotation joints rotated \( \beta_1 \) and \( \beta_2 \) from the initial position, respectively, then the firearms aiming the target. Therefore, as long as the \( \beta_1 \) and \( \beta_2 \) are known, the firearms can aim the target. Supposed that \( B'_0 \) denotes the TM from \( O'_0 \) to \( O'_1 \); \( B'_1 \) denotes the TM from \( O'_1 \) to \( O'_2 \); \( B'_2 \) denotes the TM from \( O'_2 \) to \( O'_3 \); \( 3^P = (dx, 0, 0, 1)^T \) denotes the target position in \( O'_3 \); \( dx \) denotes the distance between the target and firearms which is unknown; Then the target position within the \( O'_0 \) coordinate system \( 0^P^r \) can be expressed as:

\[ 0^P^r = B'_0 \bullet B'_1 \bullet B'_2 \bullet {}^3P^r \]
\[ (3) \]

Where, \( B'_0, B'_1 \) and \( B'_2 \) are given by:

\[ B'_0 = \begin{bmatrix} \cos \beta_1 & -\sin \beta_1 & 0 & 0 \\ \sin \beta_1 & \cos \beta_1 & 0 & 0 \\ 0 & 0 & 1 & R_{z1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \]
\[ B'_1 = \begin{bmatrix} \cos \beta_2 & 0 & \sin \beta_2 & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \beta_2 & 0 & \cos \beta_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]
\[ B'_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & R_{z2} \\ 0 & 0 & 0 & 1 \end{bmatrix} \]

where, \( R_{z1} \) and \( R_{z2} \) are constants of model parameters; \( dx, \beta_1 \) and \( \beta_2 \) are unknown quantities. By substituting \( 0^P^r, {}^3P^r, B'_0, B'_1 \) and \( B'_2 \) into Eq. (3), \( dx, \beta_1 \) and \( \beta_2 \) are calculated as shown in Eq. (4). The steering engines on the Aiming Pan/tilt are controlled to rotate \( \beta_1 \) and \( \beta_2 \), respectively, then the target is sighted by the firearms.

\[ \begin{aligned}
\beta_1 &= \arctan \frac{y_0}{x_0} \\
\beta_2 &= \pm \arctan \frac{R_{z2}}{\sqrt{r^2 - R_{z2}^2}} + \arctan \frac{R_{z1} - z_0}{\cos \beta_1 \cdot x_0 + \sin \beta_1 \cdot y_0} \\
dx &= \cos \beta_2 (\cos \beta_1 \cdot x_0 + \sin \beta_1 \cdot y_0) - \sin \beta_2 (z_0 - R_{z1}) \\
r &= \sqrt{(R_{z1} - z_0)^2 + (\cos \beta_1 \cdot x_0 + \sin \beta_1 \cdot y_0)^2}
\end{aligned} \]

4. Experimental Results

According to the structure was shown in Fig.1, Assembling the parts of the system, the overall physical structure was shown in Fig.5. The parameters were shown in Table 1. As a result of the firearm is banned in our coun-try, except in army, so the firearm was instead of the laser instrument. Supposed the laser beam denotes the ballistic trajectory, which is a straight line in our experiment. The CCD camera
provided the environmental information where people can’t reach, and the operator move the positioning unit by remote control unit, control the pan/tilt to make the white laser dot of the LR aim at the target, then the firearm of the aiming unit aim at the target automatically. The operation of the whole process is simple and flexible.

| Parameters symbol | Py | Pz1 | Pz2 | Rz1 | Rz2 |
|------------------|----|-----|-----|-----|-----|
| Values (cm)      | 40.0 | 25.0 | 10.0 | 25.0 | 10.0 |

Fig.5. Physical structure of the proposed system

Table 1. Model parameters of the proposed system.

To show the performance of the developed system, two confirmatory experiments are performed. The first experiment is that keeping pitching joint static, on the positioning unit, the horizontal joints rotate 5 degrees at a time along the two directions from the initial position, range of rotating angle was -30 to +30 degrees, the minus sign denotes clockwise direction, the plus denotes counterclockwise. Therefore, the \( d_i \), \( \theta_i \) and \( \theta_{2i} \) \((i = 1,2,\ldots,13)\) of 13 target points are obtained, by substituting these data into Eq. (2), these target positions \( 0'_{iP} \) \((i = 1,2,\ldots,13)\) are obtained, then according the Eq. (4), the \( dx_i \), \( \beta_{1i} \) and \( \beta_{2i} \) \((i = 1,2,\ldots,13)\) are calculated, the horizontal and pitching joints of the aiming unit are controlled to rotate \( \beta_{1i} \) and \( \beta_{2i} \), respectively. Finally, the laser instrument which instead of the firearm can aim at the target point. Obviously, there are a certain extent error between positioning point and aiming point, in order to quantitative analyze the error, keeping the laser instrument aiming at the current position immovably, making the spot center of laser range finder and the laser instrument located the same position by controlling the positioning unit. Then the actual coordinate \( ^0P_i \) of current position was obtained by the positioning algorithm. Supposed that \( ^0P_i = (x_i, y_i, z_i) \) denotes the aiming position, the \( ^0P_i' = (x_i', y_i', z_i') \) denotes the positioning position. The error between the two positions can be expressed as:

\[
E_i = \sqrt{(x_i' - x_i)^2 + (y_i' - y_i)^2 + (z_i' - z_i)^2}
\]

The second experiment is similar to the first one, but the only difference is that keeping horizontal joint static, rotating the pitching joint. The object is placed about 500cm, 1000cm, 1500cm in front of the device separately, the above two experiments were performed. Experiment scene as shown in Fig.6, the white and blue spot belongs to LR and laser instrument, separately.
5. Conclusion
The target positioning and aiming system and method in this paper which is based on the laser rangefinder and the 2D pan-tilt uses the limited device resources and simple calculation to reach the requirements of the target positioning and aiming in engineering. There is no doubt that there is a certain degree of tracking error in proposed system, tracking error increases as the target distance and rotated angle increase, as shown in Figure 7. The mean errors of horizontal rotation were 1.4cm, 1.7cm, 2.3cm, separately, where target at about 500cm, 1000cm, 1500cm, and the mean error of pitching rotation were 1.8cm, 2.1cm, 2.6cm. The reasons for these errors can be summarized as three aspects: (i) The parameters of the model are approximate; (ii) The low accuracy of laser ranging sensor and encoder; (iii) Structure fabrication and installation error. Despite the existence of error, however, the effectiveness of target positioning and aiming algorithm is verified. Therefore, this method can be widely used in system which has less precision in engineering applications. The measurement of data can be obtained easily. Hence, the method has a better real-time performance and operability, and this is conforming to the practical needs of engineering applications.

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