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 kinemics model of the aiming unit was built. Next, the joint angles of the steering engines on the aiming unit were computed through the tar-get position and the model. Finally, the steering engines were controlled to rotate the above-mentioned joint an-gles from the initial state, then the firearm can aim the target.
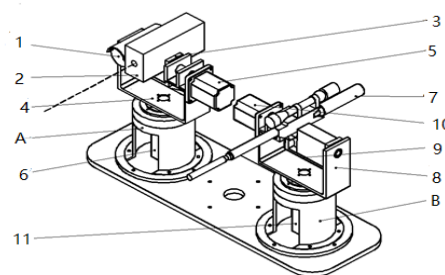
A: Positioning unit B: Aiming unit
1: CCD camera 2: Laser Range Finder 3/9: Pitch rotational structure
4/8: Horizontal rotational structure 5/6/10/11: Steering engine 7: firearm
Fig.1. Mechanical structure of the proposed target positioning and aiming System
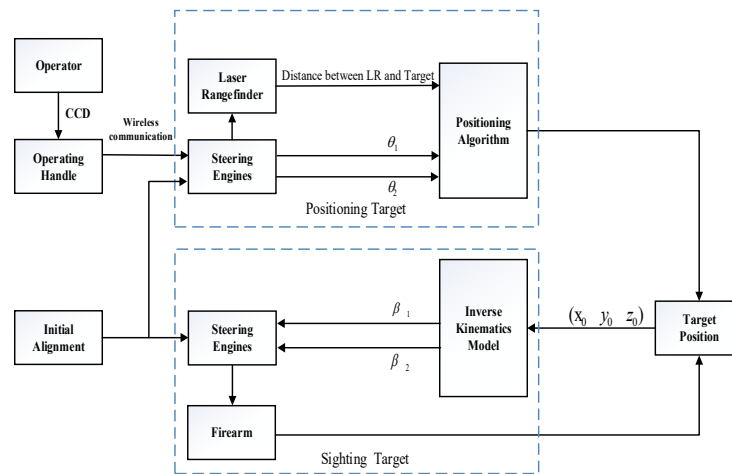
Fig.2. Overall structure of the proposed target positioning and aiming system

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 $O_0 - X_0 Y_0 Z_0$, $O_1 - X_1 Y_1 Z_1$, $O_2 - X_2 Y_2 Z_2$ and $O_3 - X_3 Y_3 Z_3$ coordinate systems are built on the Positioning unit by the D-H coordinate system defined method, respectively, Hereinafter referred to as O_0, O_1, O_2 and O_3 coordinate system. The O_0 coordinate system where in the center of the bottom of the laser positioning unit, is the basic coordinate system; The 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 θ_1 denote the horizontal rotational angle. The 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 θ_2 denote the pitching rotational angle, its origin is the same to the origin of the O_1 coordinate system. The O_3 coordinate system which is on the certain height in the Z_2 axis direction of the O_2 coordinate system, bindings in the laser range sensor, maintains translational relations with the O_2 coordinate system and therefore their motions are the same. the laser beam direction is the same to the X_3 axis direction. In the same way, the $O_0' - X_0' Y_0' Z_0'$, $O_1' - X_1' Y_1' Z_1'$, $O_2' - X_2' Y_2' Z_2'$ and $O_3' - X_3' Y_3' Z_3'$ coordinate systems are built on the Aiming unit. β_1 and β_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.
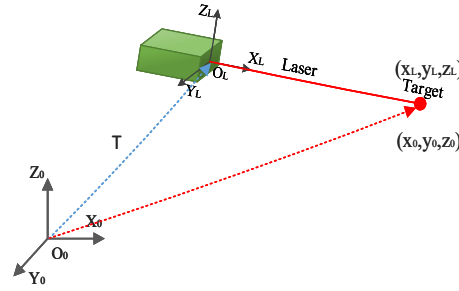
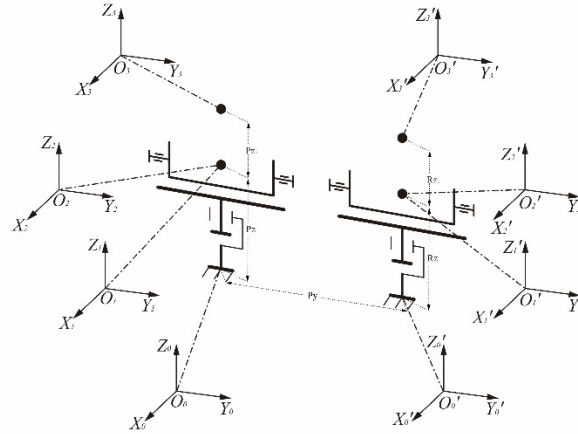Fig.3. The schematic diagram of Target positioning algorithm

Fig.4. Schematic of the coordinate system

3.2 Target Positioning Algorithm

In accordance to the transform relationship between adjacent coordinate system on the Positioning Pan/tilt. we supposed that $\mathbf{A}_{0'}^{0}$ denotes the TM from O_0' to O_0; $\mathbf{A}_0^1$ denotes the TM from O_0 to O_1; $\mathbf{A}_1^2$ denotes the TM from O_1 to O_2; $\mathbf{A}_2^3$ denotes the TM from O_2 to O_3; $^3P = (d,0,0,1)^T$ 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 $^0P'$ can be expressed as:

$$^0P' = \mathbf{A}_{0'}^{0} \bullet \mathbf{A}_0^1 \bullet \mathbf{A}_1^2 \bullet \mathbf{A}_2^3 \bullet {}^3P$$

(1)

where, $\mathbf{A}_{0'}^{0}, \mathbf{A}_0^1, \mathbf{A}_1^2$ and $\mathbf{A}_2^3$ are given by:

$$\mathbf{A}_{0'}^{0} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & Py \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \mathbf{A}_0^1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & Pz_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \mathbf{A}_1^2 = \begin{bmatrix} \cos\theta_2 & 0 & \sin\theta_2 & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta_2 & 0 & \cos\theta_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \mathbf{A}_2^3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & Pz_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

By substituting ^3P, $\mathbf{A}_{0'}^{0}, \mathbf{A}_0^1, \mathbf{A}_1^2$ and $\mathbf{A}_2^3$ into Eq. (1), the $^0P'$ is calculated by the following expression:

$$
\begin{aligned}
{}^{0}P' &= [x_0, y_0, z_0, 1]^T \\
&= [d\cos(\theta_1)\cos(\theta_2) \\
&\quad Py + Pz_2\sin(\theta_1)\,\sin(\theta_2) + d\sin(\theta_1)\cos(\theta_2) \\
&\quad Pz_1 + Pz_2\cos(\theta_2) - d\sin(\theta_2) \\
&\quad 1\,]
\end{aligned}
$$

(2)

where Py, Pz_1 and Pz_2 are constants of model parameters; θ_1 and θ_2 are obtained from the servo encoder feedback of the steering engines; d is obtained from LR. Hence, the target position ${}^{0}P'$ can be calculated.

3.3 Target Aiming Algorithm

In accordance to the transform relationship between adjacent coordinate system on the Aiming Pan/tilt. If the steering engines of the horizontal and pitching rotation joints rotated β_1 and β_2 from the initial position, respectively, then the firearms aiming the target. Therefore, as long as the β_1 and β_2 are known, the firearms can aim the target. Supposed that B_0^1 denotes the TM from O_0' to O_1'; B_1^2 denotes the TM from O_1' to O_2'; B_2^3 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 ${}^{0}P'$ can be expressed as:

$$
{}^{0}P' = \mathrm{B}_0^1 \bullet \mathrm{B}_1^2 \bullet \mathrm{B}_2^3 \bullet {}^{3}P'
$$

(3)

Where, B_0^1, B_1^2 and B_2^3 are given by:

$$
\mathbf{B}_0^1 =
\begin{bmatrix}
\cos\beta_1 & -\sin\beta_1 & 0 & 0 \\
\sin\beta_1 & \cos\beta_1 & 0 & 0 \\
0 & 0 & 1 & Rz_1 \\
0 & 0 & 0 & 1
\end{bmatrix}
\quad
\mathbf{B}_1^2 =
\begin{bmatrix}
\cos\beta_2 & 0 & \sin\beta_2 & 0 \\
0 & 1 & 0 & 0 \\
-\sin\beta_2 & 0 & \cos\beta_2 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\quad
\mathbf{B}_2^3 =
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & Rz_2 \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

where, Rz_1 and Rz_2 are constants of model parameters; dx, β_1 and β_2 are unknown quantities. By substituting ${}^{0}P'$, ${}^{3}P'$, B_0^1, B_1^2 and B_2^3 into Eq. (3), dx, β_1 and β_2 are calculated as shown in Eq. (4). The steering engines on the Aiming Pan/tilt are controlled to rotate β_1 and β_2, respectively, then the target is sighted by the firearms.

$$
\begin{cases}
\beta_1 = \arctan\dfrac{y_0}{x_0} \\[2ex]
\beta_2 = \pm\arctan\dfrac{Rz_2}{\sqrt{r^2 - Rz_2^2}} + \arctan\dfrac{Rz_1 - z_0}{\cos\beta_1 \bullet x_0 + \sin\beta_1 \bullet y_0} \\[2ex]
dx = \cos\beta_2(\cos\beta_1 \bullet x_0 + \sin\beta_1 \bullet y_0) - \sin\beta_{2*}(z_0 - Rz_1) \\[2ex]
r = \sqrt{(Rz_1 - z_0)^2 + (\cos\beta_1 \bullet x_0 + \sin\beta_1 \bullet y_0)^2}
\end{cases}
$$

(4)

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.

Table 1. Model parameters of the proposed system.

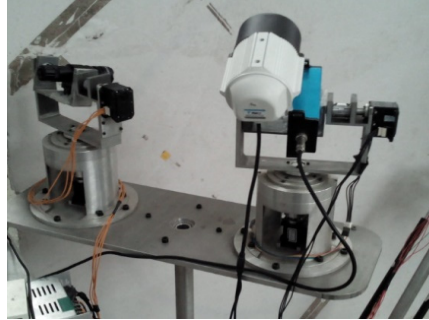| Parameters symbol	Py	Pz1	Pz2	Rz1	Rz2
Values (cm)	40.0	25.0	10.0	25.0	10.0

Fig.5. Physical structure of the proposed system

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, θ_{1i} and θ_{2i} ($i = 1, 2, ..., 13$) of 13 target points are obtained, by substituting these data into Eq. (2), these target positions $^0P_i{}'(i = 1, 2, ..., 13)$ are obtained, then according the Eq. (4), the dx_i, β_{1i}, and β_{2i} ($i = 1, 2, ..., 13$) are calculated, the horizontal and pitching joints of the aiming unit are controlled to rotate β_{1i} and β_{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:

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

(5)

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.
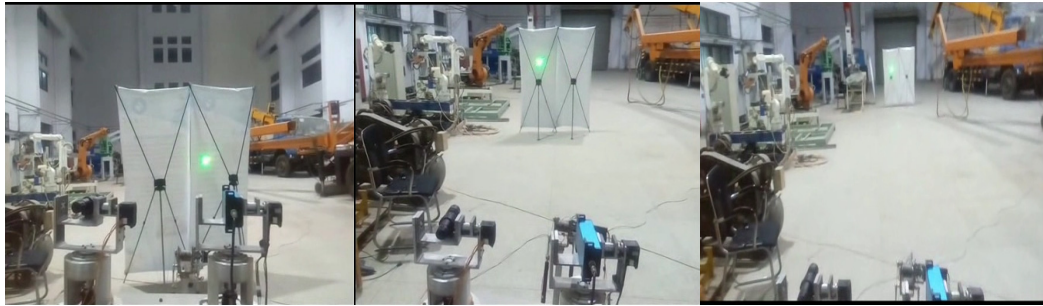
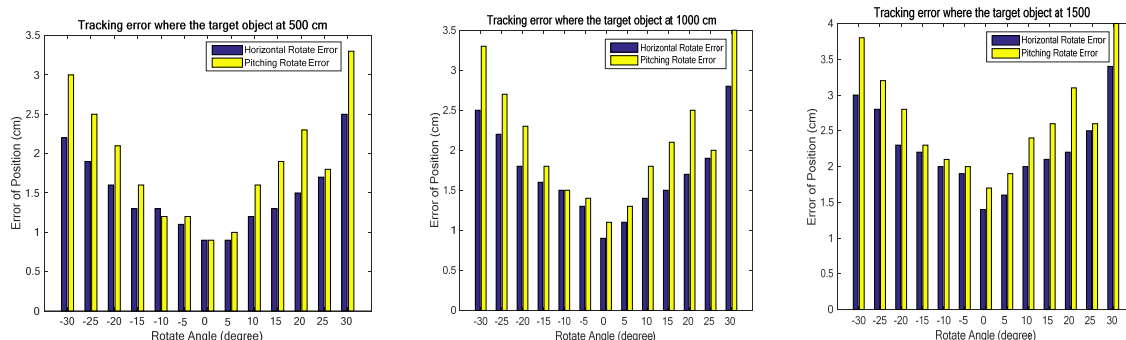Fig.6. experiment scene. Left: target at 500cm; Middle: target at 1000cm; Right: target at 1500cm

Fig.7. error between positioning and aiming position. Left: target at 500cm; Middle: target at 1000cm; Right: target at 1500cm

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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