Visual Servo Control of a Legged Mobile Robot Based on Homography

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Abstract: Due to the intermittent motion of a legged mobile robot, an additional periodic movement must be introduced that directly affects the image processing accuracy and destabilizes the visual servo control of the robot. To address this problem, this paper investigates a control scheme for the visual servoing of a legged mobile robot equipped with a fixed monocular camera. The kinematics of the legged mobile robot and homography-based visual servoing are employed to allow the robot to achieve the desired pose. By investigating the homographic relationship between the current and desired poses, the approach has no need for transcendental knowledge of the three-dimensional geometry of the target image. The feature points are directly extracted from the images to evaluate the homography matrix. To reduce the effects caused by the intermittent motions of the legged robot, an improved adaptive median filter is proposed. Furthermore, a sliding mode controller is designed, and a Lyapunov-based approach is used to analyze the stability of the control system. With the aid of CoppeliaSim software, a simulation is implemented to verify the effectiveness of the proposed method.

Keywords: Visual servo control • Homography • Sliding mode control • Legged mobile robot

1. Introduction

Legged mobile robots (LMRs) have the ability to adapt to unstructured work environments and are an important component of robotic applications. However, due to the Brockett condition [1], mobile robots need additional control information to address asymptotic stability and feedback stabilization issues related to differential geometric control theory. Thus, cameras are often used to provide the vision function for mobile robots. The vision-based control information extracted from captured images can be introduced into the robot control loop to increase the moving stability and accuracy of the system as a whole. Thus, notable advances have been made to improve what is known as visual servo control [2-5].

According to the type of visual feedback information, visual servo systems can be roughly classified into two main categories: position-based visual servoing (PBVS) and image-based visual servoing (IBVS) controls [6]. In PBVS, the controller is designed in three-dimensional (3D) Cartesian space. The 3D pose of the camera is evaluated from the visual features of the target object. In IBVS, the controller is designed directly using visual features without the need for 3D reconstruction. In addition, a combination of these two approaches also exists, which is known as hybrid or 2.5D visual servoing. In this approach, a decoupled controller can be designed by using Euclidean homography based on the estimation of a monocular displacement from the current to the desired camera poses [7, 8]. Investigations on the visual servo control of wheeled mobile robots (WMRs) have been carried out with these available methods. Based on IBVS, Wang et al. [9], presented an adaptive backstepping control law to track a moving target. Ito et al. [10], proposed a control scheme utilizing vision-based trajectory planning and tracking control to precisely generate a trajectory following a moving target. To meet field of view constraints, Xu et al. [11], developed a three-step epipolar-based visual servoing for a mobile robot. By employing a Lyapunov-based approach, Fang et al. [12], presented an adaptive estimation method for the compensation of constants and unmeasurable parameters in a homography matrix. MacKunis et al. [13], investigated the projective geometric relationships between target points in a reference image and points in a live image and proposed a hybrid visual servo control method to achieve the simultaneous tracking of two WMRs. In addition, Becerra et al. [14], proposed a sliding mode control law for mobile robots in which convergence to the target could be achieved without auxiliary images.

It should be noted that the abovementioned studies mainly focused on WMRs. Compared with WMRs, the complex mechanical structures and motion characteristics...
of LMRs pose challenges in achieving visual servo control. Due to the intermittent motion of an LMR, there is an additional periodic movement that affects the accuracy of the image processing, thereby destabilizing visual servoing. Concerning the LMR developed in our previous work [15], this paper investigates a homography-based control scheme for the visual servoing of the robot. To reduce the influence of intermittent motion on image processing, an improved median filter algorithm is proposed by considering the kinematics of the LMR. The rest of the paper is organized as follows. A brief review of the structure and kinematic analysis of the robot is introduced in Section 2. Then, an adaptive median filter is developed for pose estimation in Section 3. Section 4 addresses the design of a sliding mode controller for visual servoing. Finally, a simulation is carried out to verify the validity of the proposed control scheme in Section 5, and conclusions are drawn in Section 6.

2. Mathematical modeling

The LMR proposed in [15] is shown in Figure 1(a). This robot is composed of eight planar six-bar linkages with different arrangements. By using cylindrical and conical gears, four linkages on one side are driven by a common motor, as shown in Figure 1(b), and \( \dot{\phi} \) is the velocity of the input joint rate, while \( v_{LMR} \) is the moving speed of a group of four linkages with respect to the ground. As shown in Figure 1(b), a pair of six-bar linkages on one side of the LMR shares the same ground link and is actuated by two cranks on the same gear arranged with a phase angle of \( \pi \). Then, the steering of the robot is realized by controlling the motor speeds to achieve the difference in \( v_{LMR} \) for the two sides.

To determine the auxiliary inputs for the controller, the kinematics of the six-bar linkages are analyzed in this section. Coordinate frames are defined first to describe the motion of the robot, and then a homography model is derived to calculate the pose of the robot using the feature points of the images.

2.1 Kinematics of the LMR

Figure 2 shows a schematic diagram of the six-bar linkage consisting of a crank (link-1), a rocker (link-3), a ground link (link-4), two floating links (link-2 and link-5), and an output link (link-6). Points \( A-F \) represent the centers of the revolute joints; \( \phi \) is the input angle of the crank. A frame \( o-xy \) is established to measure all vectors, as shown in Figure 2. According to the kinematic modeling method of the Assur group presented in [15], the position vectors of points \( C, F \) and \( G \) can be directly obtained.

\[
\begin{align*}
    r_c &= r_b + q_1(r_d - r_b) + q_2M(r_d - r_b), \\
    r_f &= r_c + q_1(r_e - r_c) + q_4M(r_e - r_c), \\
    r_g &= r_c + q_3(r_f - r_c) + q_6M(r_f - r_c), \\
    q_1 &= \frac{l_{BD}^2 + l_{BC}^2 - l_{GD}^2}{2l_{BD}^2}, \\
    q_2 &= \frac{l_{BC}^2}{l_{BD}^2} - q_1^2, \\
    q_3 &= \frac{l_{EC}^2 + l_{ED}^2 - l_{EF}^2}{2l_{EC}^2}, \\
    q_4 &= \frac{l_{EC}^2}{l_{EC}^2} - q_2^2, \\
    q_5 &= \frac{l_{EF}^2}{l_{EC}^2} - q_3^2, \\
    q_6 &= \frac{l_{EF}^2}{l_{EF}^2} - q_4^2.
\end{align*}
\]
\[ q_6 = \frac{l_{EX}^2 + l_{CG}^2 - l_{CD}^2}{2l_{CF}^2}, \quad q_5 = \frac{l_{CG}^2 - l_{E}^2}{l_{CF}^2}, \]

where \( r_{2A}, r_{2B} \) and \( r_2 \) are the position vectors of points \( B, D \) and \( E \), respectively; \( l_{BC}, l_{CD} \) and \( l_{EX} \) represent the lengths of link-2, link-3 and link-5, respectively; \( l_{BD}, l_{CE}, l_{CG} \) and \( l_{FG} \) are the distances between the two points in the subscripts. Then, substituting Eqs. (1) and (2) into Eq. (3) leads to

\[
\begin{align*}
r_2 &= A r_1 + B r_4 + C r_6, \\
A &= (1 - q_1 q_3 + q_1 q_4 q_5) I \\
&\quad+ (-q_2 q_3 q_5 - q_2 q_4 q_5 + q_2 q_4 q_6 + q_2 q_3 q_5) M \\
B &= (q_2 q_3 q_5 + q_2 q_4 q_5 + q_2 q_3 q_4 + q_2 q_3 q_5) M^2, \\
C &= (q_2 q_3 q_5 - q_2 q_4 q_5 + q_2 q_3 q_4 - q_2 q_3 q_5) M^3.
\end{align*}
\]

Noting that \( r_{0A} = (l_{AB} \cos \varphi, l_{AB} \sin \varphi)^T \) and \( r_{0D} = (l_{AD} 0)^T \), Eq. (4) can be rewritten as

\[
r_2 = (l_{AB} A + l_{AD} B) u_\varphi + C r_6, \quad (5)
\]

where \( u_\varphi = (\cos \varphi, \sin \varphi)^T \) and \( r_{0D} = (l_{AD} 0)^T \); \( l_{AD} \) is the distance between points \( A \) and \( D \).

Hence, given the dimensional parameters of the links, i.e., \( l_{AB}, l_{AD}, l_{AE}, l_{BC}, l_{CD}, l_{CE}, l_{CF}, l_{FG} \) and \( l_{CG} \), and the input angle \( \varphi \), the unknown variables \( l_{BD} \) and \( l_{CE} \) can be evaluated by \( \| r_{0A} - r_2 \| \) and \( \| r_{0D} - r_2 \| \), respectively. Then, the trajectory of point \( G \) measured in \( o - xy \) can be obtained using Eq. (5).

Note that the movement of a pair of linkages with respect to the ground is a combination of two trajectories of point \( G \) in a stance phase. By defining the intersection points between the stance and swing phases as \( s_1 \) and \( s_2 \) (see Figure 2), the corresponding input angles \( \varphi_1 \) and \( \varphi_2 \) (\( \varphi_1 < \varphi_2 \)) can be evaluated using Eq. (5), respectively. Accordingly, the output trajectory \( \Omega \) (point \( G \)) of a pair of linkages can be divided into two segments.

\[
\Omega = (x_G, y_G)^T = \begin{cases} f_\varphi(\varphi) & \text{if } \varphi_1 \leq \varphi < \varphi_2, \\ f_\varphi(\varphi + \pi) & \text{otherwise} \end{cases}, \quad (6)
\]

\[
f_\varphi(\varphi) = (l_{AB} A + l_{AE} B) u_\varphi + C r_6.
\]

Furthermore, to control the locomotion of the robot, the relationship between the moving speed \( v_{LMR} \) and the velocity of the input joint rate \( \varphi \) must be established. By obtaining the derivatives of Eq. (6) with respect to time, it is convenient to obtain \( v_{LMR} \) as the component of \( \Omega \) in the direction of the \( x \) axis, i.e.,

\[
v_{LMR} = \Omega^T e_1, \\
\Omega = (l_{AB} A + l_{AE} B) u_\varphi + (l_{AB} A + l_{AE} B) u_\varphi + C r_6,
\]

\[
e_1 = (1 \ 0)^T.
\]

Eq. (7) gives an implicit expression of the velocity mapping between \( v_{LMR} \) and \( \varphi \). However, it is difficult to evaluate \( \varphi \) using this equation for a given set of \( v_{LMR} \) and \( \varphi \). To save computational cost, an iteration algorithm based on the kinematic model is proposed for the solution of \( \varphi \) (see Figure 3).

In addition, to evaluate the linear and angular velocities of the LMR, a body-fixed frame \( K \) is established at the center point \( O \) of the robot (see Figure 4). The frame of the monocular camera mounted on the robot is set to be coincident with \( K \) for simplification. With the approach, the imaging plane \( \Pi \) of the camera is perpendicular to the \( X \) axis of frame \( K \). Then, the following equation can be achieved:

\[
\begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} 1/2 & 1/2 \\ 1/L & -1/L \end{bmatrix} \begin{bmatrix} v_x \\ v_y \end{bmatrix}.
\]

Figure 3  Iteration algorithm to evaluate \( \varphi \)
moving speed $v_{L,R}$ of the group of linkages on the right (left) side.

### 2.2 Coordinate frames relationship

The purpose of this paper is to regulate the position and orientation of the LMR based on image feedback of a fixed target. In this context, the desired pose of the robot is defined by a prerecorded image of a set of coplanar feature points, $P_i (i = 1, 2, \ldots, N)$, in plane $\Pi_{obj}$ (see Figure 5). To evaluate the current pose using the homography matrix, the relationship between the current and desired poses of the robot is established in this section.

In Figure 5, frame $\mathcal{K}^*$ ($\mathcal{K}$) is defined to describe the desired (current) pose of the robot. Plane $\Pi_{obj}$ is perpendicular to the $X^*$ axis, while $n^*$ denotes its normal vector. The distance from point $O^*$ to plane $\Pi_{obj}$ is $d'$. The rotation and translation of frame $\mathcal{K}^*$ with respect to frame $\mathcal{K}$ can be obtained by

$$ R = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad T = \begin{bmatrix} T_x^* \\ T_y^* \\ 0 \end{bmatrix}, \quad \text{(9)} $$

where $\theta$ is the rotational angle of frame $\mathcal{K}^*$ with respect to frame $\mathcal{K}$; $T$ is the position vector of point $O^*$ measured in frame $\mathcal{K}$. By defining the position vector of point $O$ measured in frame $\mathcal{K}^*$ can be obtained by

$$ T^* = (T^*_x, T^*_y, 0)^T, \quad \text{(10)} $$

the current pose of the robot in frame $\mathcal{K}^*$ can be determined by a defined vector

$$ q = (T^*_x, T^*_y, -\theta)^T. \quad \text{(11)} $$

Then, the visual servoing controls the robot to reach the desired pose by achieving $q = (T^*_x, T^*_y, -\theta)^T = (0, 0, 0)^T$.

### 2.3 Visual servoing kinematics

To control the robot, the mapping between $q$ and the linear and angular velocities of the robot, i.e., $v$ and $\omega$, must be established.

The velocity of point $O^*$ with respect to frame $\mathcal{K}$ can be derived as

$$ T = -v - \omega \times T, \quad \text{(12)} $$

$$ v = (v_0 0 0)^T, \quad \omega = (0 0 \omega)^T, \quad \omega = -\dot{\theta}. $$

By expanding Eq. (12), the following expressions can be obtained.

$$ \begin{bmatrix} \dot{T}_x \\ \dot{T}_y \\ \dot{T}_z \end{bmatrix} = -v + T \omega $$

$$ \dot{T} = -RT^*. \quad \text{(14)} $$

Expanding Eq. (14) and taking derivatives of the equations with respect to time results in the velocity of the point $O^*$ measured in $\mathcal{K}$

$$ \begin{bmatrix} \dot{T}_x \\ \dot{T}_y \\ \dot{T}_z \end{bmatrix} = \omega T^*_y - T^*_y \cos \theta + T^*_y \sin \theta $$

$$ \dot{T}^*_y = -\omega T^*_y \sin \theta - T^*_y \cos \theta. \quad \text{(15)} $$

By using Eqs. (13) and (15), it can be solved that

$$ \dot{q} = Su. \quad \text{(16)} $$
\[ \dot{q} = \left( \dot{T}_x, \dot{T}_y, -\dot{\theta} \right)^T, \quad S = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad u = (v \ \omega)^T. \]

According to Eq. (16), the pose of the robot can be adjusted by vector \( u \) to accomplish the visual servoing task. To facilitate the design and analysis of the controller, we use the auxiliary error signals as the inputs of the controller. The mapping between the auxiliary error signals and the pose of the robot is given as

\[
\begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} T'_x \ T'_y \ \theta - \bar{\theta} \end{bmatrix}, \tag{17}
\]

where \( \xi_1 \), \( \xi_2 \), and \( \xi_3 \) represent the auxiliary error signals; \( T'_x \), \( T'_y \) and \( \theta - \bar{\theta} \) represent the desired pose of the robot with respect to frame \( \mathcal{K}^* \). Then, taking derivatives of Eq. (17) with respect to time and substituting Eq. (16) into the obtained equation, the visual servoing kinematics can be achieved as follows:

\[
\begin{align*}
\dot{\xi}_1 &= \omega \xi_2 + v \\
\dot{\xi}_2 &= -\omega \xi_1 \\
\dot{\xi}_3 &= -\omega
\end{align*} \tag{18}
\]

Consequently, Eqs. (11) and (18) will be used to design the controller for the visual servoing of the robot.

### 2.4 Homography calculation and decomposition

To calculate the auxiliary error signals in Eq. (17), the current pose of the robot must be obtained. In this paper, the current pose of the robot is retrieved from the current and desired images by homography calculation and decomposition.

For a set of coplanar feature points \( p_i \) on plane \( \Pi_{\text{obj}} \) (see Figure 5), two images of these points taken by the same camera at different positions (\( O \) and \( O' \)) can be geometrically related by a homography matrix \( H \) [17]. With the aid of algorithms presented in [18-20], the feature points in the imaging plane can be recognized. Let \( p_i \) and \( p'_i \) denote the pixel coordinates in two imaging planes of the current and desired poses, respectively. The mapping between \( p_i \) and \( p'_i \) can be given by

\[
\begin{align*}
p_i &= KH_{\text{obj}}^{-1} p'_i, \\
H &= R + \frac{T}{d} n^* v,
\end{align*} \tag{19}
\]

where matrix \( K \) is the intrinsic parameter matrix of the camera. Since the desired pose of the robot is fixed and the \( \chi^* \) axis is perpendicular to \( \Pi_{\text{obj}} \), both \( n^* = (1\ 0\ 0)^T \) and \( d' \) are constants during visual servoing. Then, combining Eqs. (9) and (19), the homography matrix \( H \) can be expressed as

\[
H = \begin{bmatrix} h_{11} & h_{12} & 0 \\ h_{21} & h_{22} & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \cos \theta + T_x / d' & -\sin \theta & 0 \\ \sin \theta + T_y / d' & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{20}
\]

By decomposing Eq. (20), \( T_x \), \( T_y \) and \( \theta \) can be evaluated by

\[
\begin{align*}
T_x &= (h_{11} - h_{22}) d' \\
T_y &= (h_{12} + h_{21}) d' \\
\theta &= \arctan \left( -h_{12} / h_{22} \right)
\end{align*} \tag{21}
\]

According to Eqs. (21) and (14), \( \dot{q} \) can be evaluated by the homography decomposition. Then, the auxiliary error signals can be obtained using Eqs. (14) and (17).

### 3. Adaptive median filter for pose estimation

The process of calculating the current pose of the robot assumes that the centers of the current and desired poses are coplanar. However, due to the intermittent motion of the robot, there is periodic interference affecting the image processing. Therefore, the accuracy of the estimation of the homography matrix will be reduced by the displacement of the robot in the direction perpendicular to the motion plane. To reduce this effect as well as the noise of electromagnetic interference, an adaptive median filter (AMF) is used for image processing before homography calculation, and a filter based on a median filter (MF) algorithm is employed to obtain the data of the current pose by using homography decomposition in order to enhance the stability of the images.

The standard MF for image processing is a nonlinear signal processing algorithm. The concept of the MF algorithm is to replace the center gray pixel by the median value in the window sliding in the image space. Compared with the standard MF, the AMF improves this method by adaptively changing the size of the sliding window. Hence, a smaller size filter can be used to maintain the image details with low noise, while a larger size filter is applied to remove the high noise.

By defining \( W \times H \) as the image size, \( (u_p, v_p)^T \) as the coordinate of the image point, \( S_w \) as the current window centered on \( (u_p, v_p)^T \), \( S_w \times S_w \) as the size of the current window \( S_w \), \( S_{\text{max}} \times S_{\text{max}} \) as the maximal window size, \( Z_{\text{min}} \) as the minimal gray value in \( S_w \), \( Z_{\text{med}} \) as the median of all gray values in \( S_w \), \( Z_{\text{max}} \) as the maximal gray value in \( S_w \), and \( Z_w \) as the gray value of \( (u_p, v_p)^T \), the AMF algorithm can be given as
follows:

**Process 1:** If \( Z_{\text{min}} < Z_{\text{med}} < Z_{\text{max}} \), then go to **Process 2**; otherwise, increase the window size \( w_S \). If \( w_{S_{\text{max}}} \), then repeat **Process 1**; otherwise, output \( \text{uv med} Z_{\text{med}} \).

**Process 2:** If \( \text{min} Z_{\text{min}} < \text{uv} Z_{\text{min}} < \text{max} Z_{\text{max}} \), then output \( \text{uv} Z_{\text{min}} \); otherwise, output \( \text{med} Z_{\text{med}} \).

According to the intermittent motion of the robot along the \( Z \)-axis \( B_{Z} \), the output of the AMF is redefined as

\[
\text{AMF}(u, v, \Delta v) (p, p) (g, g) (v + \Delta v, u) f = \Delta v_p \times (22)
\]

where \( f \) represents the focal length of the camera; \( \Delta v_p \) is the displacement between point \( G \) and point \( s_i \) on the trajectory \( \Omega \) of a pair of linkages on the right (left) side, which can be obtained using Eq. (6). Figure 6 illustrates the flowchart of the AMF algorithm.

Based on the concept of the standard MF algorithm, a filter is designed to process the data of the current pose obtained by Eq. (21), as shown in Figure 7. The filter sorts the collects five sets of pose data using the bubble sort algorithm [21].

### 4. Controller design

In this section, the linear and angular velocity controllers are designed to accomplish the visual servoing task using auxiliary error signals with the aid of the sliding mode control method. The sliding mode surfaces are designated as

\[
\begin{align*}
 s_u &= \xi_3 \\
 s_v &= \xi_1 - c_1 \xi_2 \text{sgn}(\omega) \\
 \text{sgn}(\omega) &= \begin{cases} 
 1 & \omega > 0 \\
 0 & \omega = 0 \\
 -1 & \omega < 0 
\end{cases}
\end{align*}
\]

where \( c_1 \) is a positive parameter; \( s_u \) and \( s_v \) represent the sliding mode surfaces of the linear and angular velocities, respectively. The exponential reaching law gives

\[
\begin{align*}
 \dot{s}_u &= -\varepsilon_0 \text{sgn}(s_u) - k_0 s_u \\
 \dot{s}_v &= -k_1 s_v 
\end{align*}
\]

where \( \varepsilon_0 \), \( k_0 \) and \( k_1 \) are positive parameters. According to Eqs (24) and (25), the controller of velocities can be designated as

\[
\begin{align*}
 \omega &= k_0 \xi_3 + \varepsilon_0 \text{sgn}(\xi_3) \\
 v &= -k_{\text{c1}} \xi_1 - k_0 \xi_2 \xi_2 \text{sgn}(\xi_3) - (\varepsilon_0 + k_0 - c_1 k_1) \xi_3 \text{sgn}(\xi_3)
\end{align*}
\]

The closed-loop kinematics of auxiliary error signals can then be obtained by substituting Eq. (26) into Eq. (18). Moreover, it is essential to prove that the controller can guarantee the asymptotic stability of the control system. The analysis is given as follows:

Select the Lyapunov function

\[
V = \frac{1}{2} (\xi_1^2 + \xi_2^2 + \xi_3^2)
\]

Taking derivatives of Eq. (27) with respect to time and substituting Eqs. (18) and (28) into the resulting equation leads to
According to the relationship of frames (see Figure 5) and Eq. (17), it is known that $\xi_i \leq 0$. Assume that $\theta$ meets the condition $|\theta| > |\varphi|$, where $\varphi = \arctan\left(-T_x/T_y\right)$. When $\theta$ does not satisfy this assumption, the rotation angle is adjusted to ensure $|\varphi| > |\theta|$. Thus, we have $\xi_i \leq 0$. Due to $\xi_i \leq 0$, $\dot{\varphi} < 0$ when $c_1k_1 < k_0 + \epsilon_0$. Hence, the stability of the control system is proven.

According to the designed controllers, the scheme developed to realize visual servo control is shown in Figure 8.

### 5. Simulation

In this section, a simulation is carried out to verify the validity of the proposed control scheme. A virtual model of the robot having the same dimensions as the prototype is built in the environment of the commercial software CoppeliaSim. The vision sensor provided by the software serves as the camera to obtain the target image. The control scheme is written in C++ and enabled to control the virtual model via the Remote API of the software.

As shown in Figure 9, the setup of the simulation includes the model of the robot with a vision sensor and a target image having six red circles. With respect to the global frame $K_x$, defined in the software, the target image is fixed at $(1.4 \, m \, 0 \, 0.15 \, m)^T$; another vision sensor is placed at $(1 \, m \, 0 \, 0.15 \, m)^T$ to provide the reference image; the initial configuration of the robot is $(0 \, 0.3 \, 0.15 \, m)^T$ and $\theta = 25^\circ$. Table 1 lists the dimensional parameters of the robot, and Table 2 lists the size of the image and the parameters of the vision sensor and controller.

Figure 10(a) shows the photographs of the simulation, in which the robot moves from the initial pose to the final pose, and Figure 10(b) shows the corresponding images captured by the vision sensor fixed on the robot. Figure 11 illustrates the variations of the linear and rotational velocities generated by the controller designed in Section 4. It can be seen that their variations are within reasonable ranges during the simulation. Figure 12 shows the comparison between the obtained position and orientation of the robot with respect to frame $K_x$ and their desired values. The root mean squared errors (RMSEs) between the simulated and the desired values of $x$, $y$ and $\theta$ are $0.0275 \, m$, $0.0119 \, m$ and $1.4375^\circ$, respectively, while the error at the final pose is $(-0.0401 \, m, -0.0044 \, m, 1.6614^\circ)^T$.
The reason for the fluctuation of $\theta$ is that the update frequency of the control law is not fast enough to adjust the variation of the angular velocity. The simulation results demonstrate that the proposed control scheme can be effectively used for the visual servoing of the robot.

6. Conclusion

Investigation on the visual servo control scheme of a legged mobile robot is presented in this paper. The following conclusions are drawn.

(1) Kinematic analysis of the LMR is carried out to establish the relationship between the linear and angular velocities and the motor speeds of the robot.

(2) Aiming at reducing the effects of the interference caused by the intermittent motion of the robot on estimating the homography matrix, an improved median filter is designed.

(3) Based on the sliding mode control method, a controller is designed to generate the linear and angular velocities of the robot by using the auxiliary error signals, and the stability of the control scheme is verified.

(4) A simulation is implemented to demonstrate the validity of the proposed control scheme using
CoppeliaSim software. The results show that the proposed method can effectively control the LMR to reach the desired pose.

7 Declaration

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Availability of data and materials
The datasets supporting the conclusions of this article are included within the article.

Authors’ contributions
Haitao Liu was in charge of the whole trial; Dewei Zhang wrote the manuscript; Xianye Wang assisted with the process of analysis; Juliang Xiao provided the assistance of theory. All authors read and approved the final manuscript.

Competing interests
The authors declare no competing financial interests.

Consent for publication
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Not applicable

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