Camera Control for Active Surveillance from a Six-Leg Walking Machine

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Abstract - **In this paper we present a kinematic description of a six-legged laboratory prototype robot and control algorithm for tracking a target from the robot using active camera. The hexapod hardware platform with fluidic muscle is described. We present an algorithm that provides automatic control of a tilt camera to follow a target and keep its image centered in the camera view. An error coordinate defined in the image plane and representing the target offset with respect to the center of the image is used for camera control. Simulation results are presented to illustrate the effectiveness of the proposed control law.**

I. Introduction

Legged vehicles have a number of potential advantages over wheeled or tracked vehicles for locomotion over rough terrain. This is a result of the abilities of legs to use discrete foot-terrain interactions and to adapt to the terrain which permit the vehicle body to move smoothly over the surface while legs absorb or avoid terrain irregularities. Six legged locomotion is the most popular legged locomotion concept because of the ability of static stable walking. The hexapods are often inspired by nature, two examples of such robots are Lauron [1] and Genghis [2]. Most of them are laboratory prototypes [3,4,5], but there are also few walking machines built for specific applications, such as SILO06 [6], a six-legged robot built for humanitarian demining.

In recent years, target detection and tracking has been an important research topic in computer vision. The use of autonomous active camera as opposed to fixed cameras extends the range of sensing and effectiveness of the systems. However, the task of target tracking with moving camera is much more complex than the tracking from a fixed camera and effective tracking in a such scenario remains a challenge. While there has been significant amount of work on target tracking from the single static camera, there has been much less work on tracking using active cameras, [7,8]. The adequate control of the camera is an essential phase of the tracking process. In [9,10], a camera is used for navigation of legged robots. In [11], a PI-type controller was proposed for a pan-tilt camera.

In this paper, we present an algorithm that provides automatic control of a tilt camera to follow a target and keep its image centered in the camera view.

Our approach to the target tracking is to design a control scheme using visual information only, without long-term prediction of the target motion, which is unknown in advance and may be characterized by sudden changes. An offset (error) vector defined in the image plane and representing the coordinates of the target with respect to the image frame is used for camera feedback control. The proposed control law achieves ultimate boundness of the closed-loop system. Stability analysis of the closed-loop system is performed.

The rest of the paper is organized as follows: Section 2 describes the mechanical design of the hexapod with pneumatic muscles. In Section 3, a kinematic description of the robot is presented. In Section 4, we present the feedback tracking controller for the camera. We provide simulation results in Section 5. Conclusions are presented in Section 6.

II. The Hexapod Prototype

Our six-legged walking robot prototype is shown in Fig. 1.

Fig.1 The six-legged robot prototype

The leg weighing 1,6 kg is structured in three segments thus matching the biological pattern leg. The leg's locomotion is secured by a total of six FESTO provided fluid muscles:

- two DMSP-10 type fluid muscles for motioning the θ_1 - joint with a length of 120 mm and maximal force of approx. 230N;
- two DMSP-20 type fluid muscles for motioning the θ_2 - joint with a length of 115 mm and maximal force of approx. 670N;

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- two DMSP-10 type fluid muscles for motioning the θ_3 -joint with a length of 140 mm and maximal force of approx. 260N.

The muscles are capable of contracting to 80% of the overall length under a provided 6-ba-ressure. The actuating of one joint is achieved through two of the muscles under implication of the antagonistic connection principle [4]. Each of the legs is attached to the body in a 60° angle (Fig. 1). The body features following dimensions: length approx. 500 mm, width 250 mm and height 300 mm. For the eventual variant of the robot a weight of about 12 kg is pursued.

III. Robot Kinematic Equations of Motion

In this paper, we consider a walking robot with six identical legs equally distributed along both sides of the robot body in three opposite pairs.

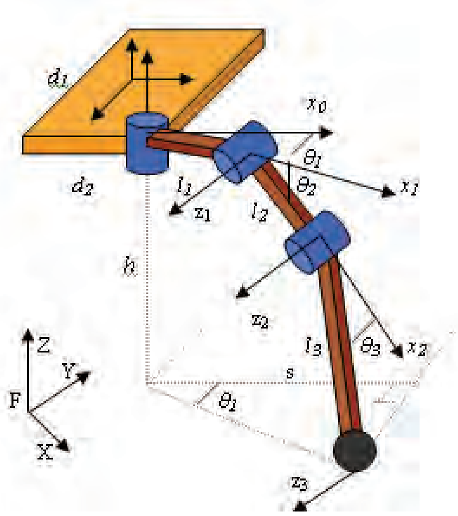

Fig. 2 Link frame attachment to the 3 degrees-of-freedom leg

Each leg consists of three links and three revolute joints as shown in Fig. 2. The link parameters of each leg are denoted as follows: θ_i, $(i = 1,2,3)$, are joint variables, and l_i , $(i = 1,2,3)$, are the lengths of the links (Fig. 2). The first two (thoracic denoted by θ_1 and hip denoted by θ_2) are orthogonal to each other, and the third (knee denoted by θ_3) is parallel with the second. In our previous paper [12], the Denavit-Hartenberg convention was used for kinematic modeling. The inverse kinematics problem, i.e., the problem of finding the joint variables in terms of the top position was also solved. The inverse kinematics of the robot are used to obtain the joint angles for each of the legs from the desired changes in the robot heading and displacement and is essential for foot placement algorithms, trajectory planning, obstacle avoidance, etc. **E**xpressions for the two joint angles θ_2 and θ_3 as functions of the thoracic joint angle θ_1 were also obtained in the form:

$$\theta_2 = 2a\tan\left(\frac{b}{a+c} + sqrt[(\frac{b}{a+c})^2 - (\frac{c-a}{c+a})]\right) \quad (1)$$

$$\theta_3 = -\theta_2 + a\sin[\frac{1}{l_2}(\frac{s}{\cos\theta_1} - l_0 - l_1\cos\theta_2)] \quad (2)$$

where

$$a = \frac{2l_1}{l_2^2}(l_0 - \frac{s}{\cos\theta_1}); \qquad b = \frac{2Hl_1}{l_2^2};$$

$$c = 1 + \frac{2l_0 s\cos\theta_1 - s^2}{l_2^2\cos^2\theta_1} - \frac{H^2 + l_0^2 + l_1^2}{l_2^2};$$

and H is the body height and s is the foot distance (Fig.2). We also define the angle θ_{3adj} as

$$\theta_{3adj} := \pi/2 - \theta_3 \qquad (3)$$

which is used in the simulations, since θ_3 is often grater than $\pi/2$. Angle θ_{3adj} is the angle between the perpendicular with respect to axis x_2 and axis x_3.

4. The Active Camera Control Law

In this Section, we consider the problem of controlling the motion of a tilt camera. We are dealing with a dynamic environment, and the control objective is to maintain the target being tracked in the center of the camera view. During this process, the acquired images are post-processed in order to retrieve the coordinates of the target with respect to the image plane (target offset). A simple kinematic model of the camera is developed which is used for the design of the camera feedback tracking controller.

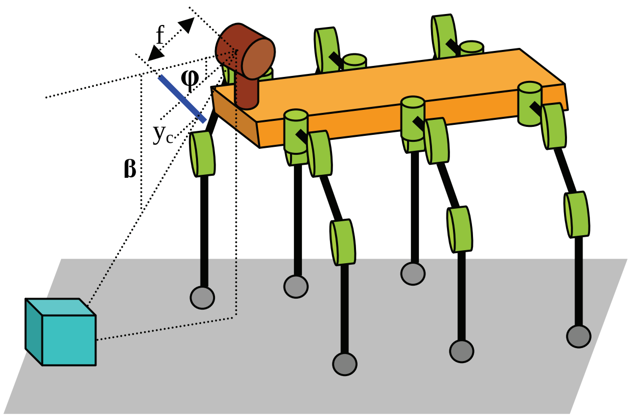

Fig. 3 Dependence of the target coordinate y_c on the tilt angle φ

The proposed feedback control makes use of visual information only and does not need long-term prediction of the target motion motivated by the potential application in which the target motion is unknown in advanced and may be characterized by sudden changes.

Since we want to track the center of the target, let $q = [x_c, y_c]^T$ be the target offset with respect to the center of the image. For the design of the tracking controller, we make the following assumption: The intersection of the tilt and camera axes coincides with the focus of the camera (Fig. 3).

Let f be the camera focal length. The following equation holds for the dependence of image coordinate y_c on the tilt angle φ.:

$$y_c = f\tan(\beta - \varphi) \qquad (4)$$

Differentiating (4), a kinematic model for the y_c offset is obtain in form

$$\dot{y}_c = \frac{f}{\cos^2(\beta - \varphi)}(\dot{\beta} - \dot{\varphi}) \qquad (5)$$

where the pan velocity $\dot{\varphi}$ is considered as a control input. The term $\dot{\beta}$ depends on the instantaneous motion of the target with respect to the frame $F_rX_rY_r$ attached to the robot, and can be computed numerically (via finite difference) from (4). We propose a control law in the form

$$u_\varphi := \dot{\varphi} = \dot{\beta}_n + c_\varphi y_c \qquad (6)$$

where $c_\varphi = cte > 0$ and $\dot{\beta}_n$ is computed numerically.

In practice, the forward term $\dot{\beta}_n$ is only approximately known. In order to evaluate the effect of using an approximate value of $\dot{\beta}$ on the comportment of the closed-loop system, we apply (6) to the control system (5). The resulting closed-loop system is

$$\dot{y}_c = \frac{f}{\cos^2(\beta - \varphi)}(-c_\varphi y_c + \xi) \qquad (7)$$

where $\xi = \dot{\beta} - \dot{\beta}_n$ is a bound function of time.

Using the quadratic positive definite function $V = (½)y_c^2$, its derivative $\dot{V}$ along the solutions of (4) is obtained in the form

$$\dot{V} = y_c\dot{y}_c = \frac{f}{\cos^2(\beta - \varphi)}(-c_\varphi y_c^2 + y_c\xi) \qquad (8)$$

In this case, the objective of guaranteeing global boundedness of solutions can be equivalently expressed as rendering $\dot{V}$ negative outside a compact region. Using the Young's inequality $(xy \le kx^2 + (1/4k)y^2)$ with $k = 1$, we obtain

$$\dot{V} \le \frac{f}{\cos^2(\beta - \varphi)}(-(c_\varphi - 1)y_c^2 + \frac{1}{4}\xi^2) \qquad (9)$$

Referring to (15), we see that $\dot{V}$ is negative whenever $|y_c| \ge \frac{\xi}{2\sqrt{c_\varphi - 1}}$. Since ξ is bounded, we conclude that $\dot{V}$ is negative outside the compact set

$$S = \left\{ y_c : |y_c| \le \frac{\|\xi\|_\infty}{2\sqrt{c_\varphi - 1}} \right\} \qquad (10)$$

Recalling that $V = (½)y_c^2$, we conclude that $|y_c(t)|$ decreases whenever $y_c(t)$ is outside the set S, and hence $y_c(t)$ is bounded:

$$\|y_c\|_\infty \le \max\left\{ |y_c(0)|, \frac{\|\xi\|_\infty}{2\sqrt{c_\varphi - 1}} \right\} \qquad (11)$$

V. Simulation Results

Our model was simulated on a flat floor. The robot parameters were chosen to be (Table I).

TABLE I
LENGTH OF THE LINKS OF EACH LEG

link	1	2	3
length	0.07[m]	0.285[m]	0.31[m]

The body length is $d_1 = 0.56m$ and body base $b_2 = 0.24m$. During each stance the lateral distance between body and foot and the height of the body above the ground remain constant. The simulations are performed (for the support phase) for walking at a constant height $H = l_3$. For the simulations, we use the inverse kinematic solution to compute the joint angles of the leg based on the desired change in the longitudinal direction of the robot during the support phase of the leg. The simulation are performed in the case when the legged robot has to move forward for total of $d=d_{max} = 0.208m$ The camera is mounted on the robot at a *0.5m* from the ground.

In this section, we present some simulation results in order to evaluate the effectiveness of the proposed control for the camera mounted on the robot.. For illustration, we consider the dependence of y_c on the tilt angle φ. The available information is the y_c offset observed by the camera in the image plane coordinate system. We assume a camera with a focal length of *3mm.*We also assume that the point where the tilt axis intersects the camera axis coincides with the focus of the camera. For the simulation purposes, the offset y_c is evaluated directly in millimeters (*mm*) instead of pixel representation in order to avoid the transformation procedure related to the scaling factors (for a concrete camera) in the intrinsic camera calibration matrix.

In the first simulation, the target is motionless and it is situated a distance of 2m from the robot. The angle $\beta = 0.25rad = cte$ (Fig. 3) which corresponds to the initial value of $y_c(0) = 7{,}5.10^{-4}$m. Initially, the tilt angle $\varphi(0) = 0$. The control law was in the form (6) with $\dot{\beta}_n = 0$. The gain c_φ used in the control law was chosen to be: $c_\varphi = 150$. The camera successfully hunts the target and places it at the center of the image plane zeroing the offset y_c. Evolution of the target offset y_c along the *y*-axis in the image plane and evolution of the tilt angle φ (solid line) and angle β (dashed line) are shown in Fig. 4 and Fig. 5, respectively.

In the second simulation (Fig.6 and Fig. 7), we assume that the target is motionless, initially placed a *2m* away from the robot, and the legged robot is moving straight at a speed of 0.*1m/s = cte.*

VI. Conclusion and Future Work

In this paper, the mechanical description of a six-legged robot with fluidic muscles was presented. An algorithm that provides automated control of a tilt camera to follow a target and keep its image centered in the camera view has been proposed. The control scheme for target tracking uses visual information only (an offset vector defined in the image plane). Feedback camera control design and stability analysis have been performed. It should be noted that at present stage this paper must be regarded as a preliminary report of our research. The experimental legged robot is under construction.

Future work will involve developing of a robot dynamic model, dynamically-based motion control algorithms for tracking moving objects, and experimental results.

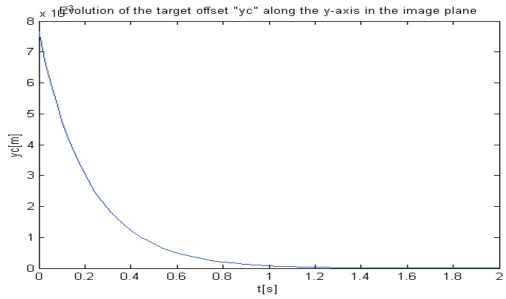

Fig.4 Motionless target: evolution of the target offset y_c along the y-axis in the image plane

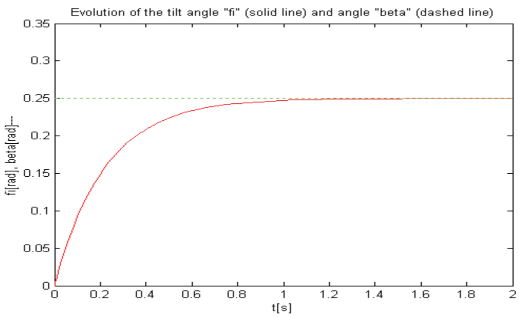

Fig.5 Motionless target: evolution of the tilt angle φ (solid line) and angle β (dashed line)

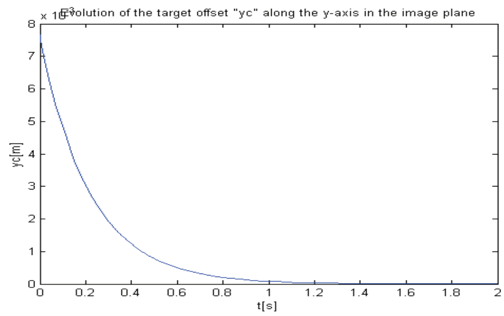

Fig.6 Motionless target and rectilinear motion of the robot at a rate of 0.1m/s. Evolution of the target offset y_c along the y-axis in the image plane

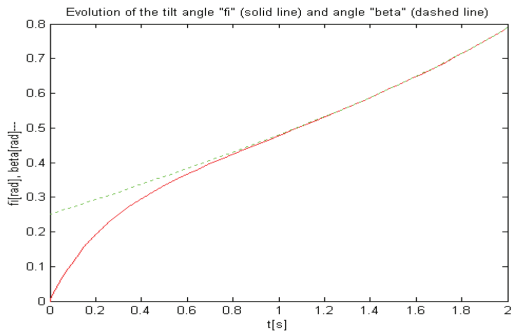

Fig.7 Motionless target and rectilinear motion of the robot at a rate of 0.1m/s. Evolution of the tilt angle φ (solid line) and angle β (dashed line)

In this case, $\dot{\beta}$ can be calculated exactly, since the target is motionless. The initial condition are as follow: angle $\beta(0)$ = *0.25rad* and the tilt angle $\varphi(0) = 0$ which corresponds to the initial value of $y_c(0)$ = 7,5.10^{-4}m. The control law was in the form (3). The control gain c_φ was the same as in the first simulation ($c = 150$).

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