Local Vision-Based Tether Control for a Line of Underwater Robots

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***Abstract*— Remote Operated Vehicles are widely used in underwater operation mainly because the tether that links the robot to its floating base provides inexhaustible energy and gives live feedback which alleviates two major issues in autonomous underwater vehicles : autonomous decision making and power consumption. Yet deploying and handling a tether is not without drawbacks. Tether dragging or entanglement can hamper the ROV motion and it could make it difficult to navigate in narrow and confined spaces such as wreck or cave. In this paper we introduce the concept of line of ROVs : adding intermediate robot along the tether can be a simple and practical solution to properly handle tether shape. In this paper we propose to investigate the use of a local visual servoing.**

I. Introduction

Tethered and umbilical systems linking mobile robots are used for power transmission, communication and mechanical assistance. Tether shape management is a challenging problem, which is addressed in several fields of applications, such as planetary exploration [1], [2], underwater missions [3] and rescue operations [4]. A large number of tethered robots use mechanical systems to manage the tether [4]–[6], while some other systems combine mechanical and vision-based approaches to accomplish the task [1]. Cable management systems are also found in the context of object transportation and cable-driven parallel robots [7]–[10].

We designed a visual servoing control scheme for catenary-shaped deformable objects to control the shape of a sagging tether linking a follower robot to a leader exploration robot [11]. Catenary parameters were estimated from the tether points captured by a camera embedded on the follower robot and used to achieve an eye-in-hand visual servoing control. This control scheme allowed to position the follower robot with respect to the tether plane and to control the tether slackness.

In order to handle the tether in confined environments, we introduce the concept of line of robots: several identical ROV of same capability are regularly fixed to the tether. Each of them is dedicated to control a local portion of the tether. The aim is to conform locally the tether to desired 3D shapes so that its global 3D shape is such that it avoids entanglements with obstacles or with other fellow robots during teleoperated missions.

In order to fully constrain the configuration of a robot pair we will implement a hierarchical control scheme to regulate the follower robot motion depending on the tether slackness and orientation w.r.t. each robot. Then, we will investigate the sequential use of the local visual control [11] for pairs of robots in a robot line.

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II. Method

A. Variable and Frame definition

Figure 1 depicts the frames and variables associated to the proposed tether handling system setup. The robot r_2 has to ensure that the tether portion between frames Σ_1 and Σ_2 is slack enough not to hamper the motion of robot r_1 nor entangle with obstacles.

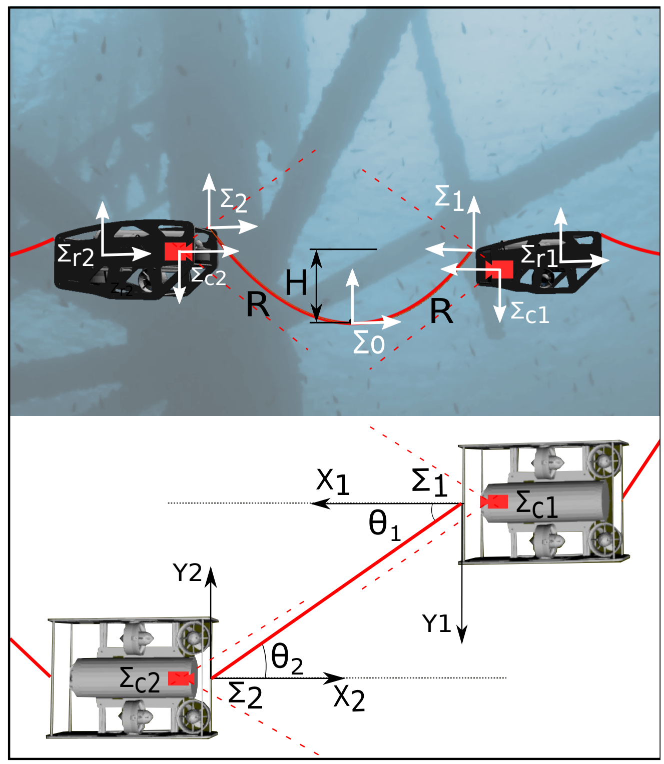

Fig. 1: The setup of the tether handling system for terrestrial robots. A leader (r_1) and a follower (r_2) mobile robots are linked by a sag tether.

Let r_i, $i \in 1, 2$ be the leader and the follower robots, respectively. Let c_i be the cameras embedded on the i^{th} robot. Each camera captures the image of an extremity of the tether linking both robots, whose associated attachment points are noted Σ_i. The tether is passive and its length is $2R$. If the tether has a slightly negative buoyancy, we can model its shape by a catenary, parametrized by its slackness H and its orientation with regards to the robots frames $b_i = \sin(\theta_i)$.

$$L_2 = \begin{bmatrix} -\frac{K_H\sqrt{1-b^2}}{2H_{max}} & -\frac{K_H b}{2H_{max}} & 0 & 0 & 0 & \frac{K_H\left(Y_1\sqrt{1-b^2}-X_1 b\right)}{2H_{max}} \\ -\frac{b\sqrt{1-b^2}}{2D} & \frac{-1+b^2}{2D} & 0 & 0 & 0 & -\frac{Y_1 b\sqrt{1-b^2}+X_1(1-b^2)}{2D} \end{bmatrix} \tag{1}$$

B. Local visual servoing for tether shape regulation

The visual servoing scheme designed for parametric deformable catenary in [11] regulates the features $s_2 = [a_2, b_2]$ related to the follower orientation $b_2 = \sin(\theta_2)$ and the tether slackness $a_2 = \frac{H}{H_{max}}$ using an on-board camera, assuming that the leader robot is fixed. The interaction matrix L_2 is derived for a catenary shaped deformable tether, at its attachment point Σ_2 :

$$\dot{s_2} = \begin{bmatrix} \dot{a_2} \\ \dot{b_2} \end{bmatrix} = L_2 v_2^F \tag{2}$$

where v_2^F is the velocity vector of the tether attachment point at the follower robot and L_2 is the interaction matrix that relates the follower robot motion with the shape evolution of a catenary projected in the follower view. The matrix L_2 is expressed by Eq. (1), where (X_1, Y_1, Z_1) are the coordinates of Σ_1 expressed in the frame Σ_2, $K_C = -\frac{2\left(R^2+H^2\right)}{(R^2-H^2)^2}$, $K_H = \frac{sinh(CD)}{1+\frac{K_C}{C^2}[\cosh(CD)-1-CD\sinh(CD)]}$ and $C = \frac{2H}{R^2-H^2}$.

From Eq. (2) we can deduce the following proportional control law [12], [13]:

$$v_2^F = -\lambda_2 L_2^+(s_2 - {s_2}^*) = -\lambda_2 L_2^+ e_2 \tag{3}$$

where $\lambda_2 \in \mathbb{R}^+$.

Yet, if the leader robot moves, $\dot{s_2}$ depends not only on the velocity of the follower robot attached point but on the relative velocity of both attached points. Actually, if the leader moves, the feature motion would be

$$\frac{\delta s_2}{\delta t} = -L_2{}^2V_1 v_1 \tag{4}$$

where ${}^2V_1$ is the twist matrix related to the transformation between the frames Σ_1 and Σ_2.

Then the complete model of the time variation of the feature s_2 can be written:

$$\dot{s_2} = -\lambda_2 e_2 = L_2 v_2^F + \frac{\delta s}{\delta t} = L_2 v_2^F - L_2{}^2V_1 v_1 \tag{5}$$

This correction can be included as a correction in the controller which becomes:

$$v_2^F = -\lambda_2 L_2^+(e_2 + L_2\widehat{{}^2V_1}\widehat{v_1}) \tag{6}$$

with $\widehat{{}^2V_1}$ and $\widehat{v_1}$ are some estimation of the leader robot velocity and the relative position of the points.

C. Adding another camera to catch the orientation of the leader

In order to navigate in narrow or confined environments, the relative position of the two robots must be fully constrained. In this case, the distance between the two attachment points $(2D)$ as well as the two relative angles between the robots orientation and the tether plane (θ_1 and θ_2) have to be regulated. Adding a camera on the leader robot allows to track the tether projection from the leader point of view.

Since the tether shape only depends on the relative position of the two attachments points, the variation features s_1 can be deduced from the motion of the follower robot and the control law can be written easily

$$v_2^L = \lambda_2{}^2V_1 L_1^+(s_1 - {s_1}^*) = \lambda_2{}^2V_1 L_1^+ e_1 \tag{7}$$

D. Stacking the tasks to fully constrain the two robots

If the follower robot has enough degrees of freedom, we can even set up a two-tasks control scheme, with a higher priority for either the tether-follower or the tether-leader orientation control, depending on the situation: obstacle avoidance will need a higher priority on the leader-tether angle whereas keeping the tether in the follower view is more important most of the time.

In free places, the leader-tether angle constraint could even be relaxed to minimize the distance to be traveled by the follower. Then, we propose to use a stack of tasks [14] that can be re-ordered depending on the situation at hand, considering that the slackness handling is a first task, and the two orientations are two other separated tasks.

We could also add some other constraints to ensure that the tether is neither degenerated nor out of the view.

In order to regulate properly the three tasks $b1$, $b2$, and a, we can either add a line to the interaction matrix L_2 and converge to a trade-off between all the desired features, or split the interaction matrix into two lines and implement a hierarchical control scheme to give them the suitable priority with regards to the task at hand: path following, obstacle avoidance, station keeping.

Let $L_a = L_2(1)$ be the interaction matrix for the rope slackness and and $L_{b2} = L_2(2)$ be the interaction matrix to control the follower robot orientation.

For example, the regulation of the slackness a be the task of higher priority and b_2 the second and b_1 the third, then the control scheme can be rewritten:

$$\begin{aligned} {v_2}^{a21} = &-\lambda_a L_a^+(a - a^*) + P_a(-\lambda_2 L_{b2}^+(b_2 - {b_2}^*) \\ &+ P_{b2}(\lambda_1 * {}^2V_1 * L_{b1}^+(b_1 - {b_1}^*))) \end{aligned}$$

where $P = I - L^+L$ is a projector on the null space of the task Jacobian L.

III. Simulation Results

The simulation results are presented in Fig. 2. We tested two hierarchical control. In both cases, the tether sag H is the higher priority task. For the first controller, θ_2 regulation is the secondary task and θ_1 is the third task, whereas in the second controller $\theta 1$ is regulated with higher priority than

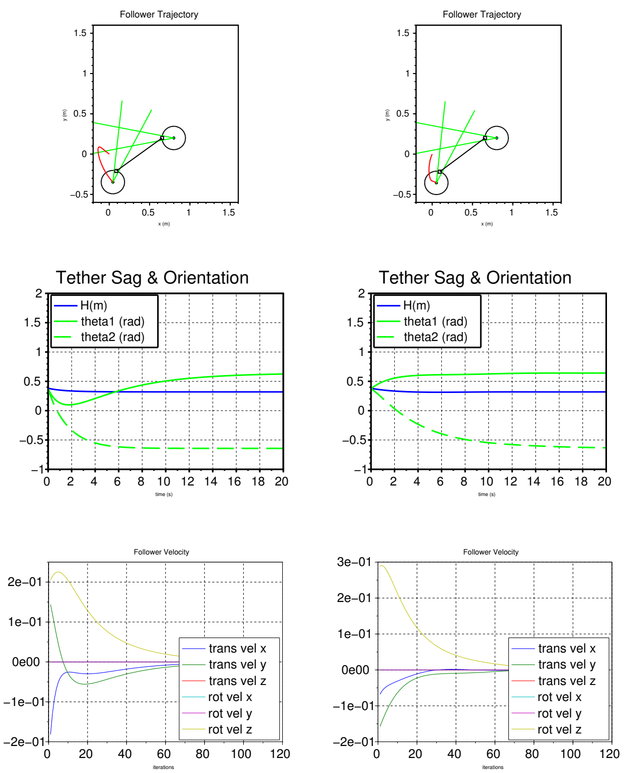

Fig. 2: Comparison between two hierarchy control schemes for tether handling purposes : the left side depicts the behavior of the follower robot for a fixed leader and a higher priority on the follower orientation ; on the right side, a higher priority is given to the relative orientation of the tether w.r.t the leader, which strongly constrains the position of the follower robot.

θ_2. Since θ_1 is regulated by the follower, this control induces large translational motion. On the contrary, the regulation of θ_2 mainly demands rotation along the z axis. Controlling θ_2 will mainly insure that the tether is kept in the camera field of view, while θ_1 will be dedicated to position the follower relatively to the leader. In this simulation, for both controllers, the tether initial slackness is $H = 0.4$m and initial orientation angles are $\theta_i = 0.4rad$. The desired tether shape parameters are $H^* = 0.32$m, ${\theta_1}^* = 0.6rad$ and ${\theta_2}^* = -0.6rad$.

In the first controller the secondary task, θ_1 regulation, is only active if it does not disturb the main task. In the figure, we can clearly see the regulation of the two tasks: θ_2 is regulated first and θ_1 reaches its targeted value and the main task is accomplished. The second controller prioritizes the regulation of θ_1. The two tasks can be reordered accordingly to the robot mission.

IV. Conclusions and Perspectives

This paper studied vision-based control strategies that can be used to manage the shape of a tether linking a line of robots. A new visual servoing scheme was also proposed in order to fully constrain the tether handling system, namely the tether slackness and its orientation angles with respect to both robots. Future work will extend tether visual servoing control to 3D through the management of vertical translation and pitch rotation. One target application will be the displacement of a line of tethered robots inside a cluttered environment such as oil and gaz station wreck or natural cave.

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