External Hybrid Vision/Force Control

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***Abstract*— Combining vision and force data in a closed loop feedback control system becomes extremely important if the task requires the tools to come into contact with the external environment. Two different approaches for vision/force coupling have been defined in the literature: hybrid-based and impedance-based control. In this paper, we make an overview of these approaches and show their main drawbacks. For hybrid-based control, an accurate model of the task is needed, whereas in impedance-based control, local minima can appear and the system may not converge. In order to solve these problems, we propose a new method for vision/force coupling, namely external hybrid vision/force control. In our scheme, the vision control loop is put inside an external force control loop in a hierarchical way. Coupling is done in sensor space: the reference trajectory generated by visual control is modified by the force control loop. A detailed comparison with the existing strategies show how the external hybrid control is able to converge where the other methods fail.**

***Index Terms*— hybrid control, visual servoing, force control**

I. INTRODUCTION

Many robotic tasks require the robot end-effector to operate in unknown and/or dynamic environments. To deal with such tasks, external sensors such as cameras and/or force sensors play a central role. Indeed, vision sensors can provide a rich knowledge about the spatial arrangement of the environment and the force sensors can provide local information to eventually correct the 3D trajectory of the robot when it comes into contact with an object.

When dealing with disparate sensors, a fundamental question stands: how to effectively combine the measurements provided by these sensors? An approach of this problem is to combine the measurements using multi-sensor fusion techniques [2]. However, as pointed out by several researchers, such method is not well adapted to vision and force sensors since the data they provide measure fundamentally different physical phenomena, while multi-sensory fusion is aimed in extracting a single information from disparate sensor data. Another approach to this problem is to combine visual and force data at the control level.

Many researchers have addressed the use of force sensors in feedback control loop [10], [18], [13], [19]. Standard approaches couple force control to position control. They are generally classified in two groups namely hybrid-based and impedance-based position/force control [9].

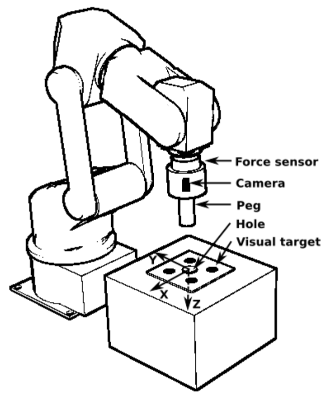


Fig. 1. General setup for the vision/force controlled task

The first scheme is a parallel architecture. Forces are controlled along constrained directions while the position feedback controls the remaining degrees of freedom. In this approach it is necessary to ensure orthogonality between the outputs of force controller and position controller to avoid any conflict at the actuator level. The range of feasible tasks is reduced to those that can be described in terms of constraint surfaces. Furthermore, if a perturbation occurs along the force controlled direction, the induced positioning error can not be corrected.

The second approach is a way to provide the end effector with a programmable mechanical impedance. The resulting control law is composed of two terms. The first one allows to servo the robot trajectory to a reference one and the second acts with respect to the programmed impedance when a contact arise. The total control law can potentially lead to a local minima since the effects of the two terms can eventually be opposed. Moreover, due to the difficulties in programming impedance controlled manipulators, this strategy has been exploited in very limited application.

Both schemes require in general geometrical knowledge about the workpiece in order to position accurately the robot. To overcome this deficiency, the use of vision control loop instead of the position one have been investigated. Indeed, computer vision can provide a powerful way of sensing the environment and can potentially reduce or avoid the need for environmental modeling. Vision allows accurate part alignment in partially unknown and/or dynamic environments without requiring contacts. Force sensor provides localized but accurate contact information. It allows to eventually correct the trajectory provided by the vision controller when contacts occur.

To combine visual and force information at the control level, two main approaches (impedance-based and hybrid-based strategies) have been studied [7], [15], [5], [1]. In these schemes the idea is merely to replace the position controller by a vision-based controller. These approaches share thus the same drawbacks than the corresponding position/force schemes.

In this paper we present a new scheme, based on the concept of external control [17], to combine vision and force control in order to solve the deficiencies in current approaches. In our control scheme, force and vision controllers are superposed. The hierarchical juxtaposition of the force control loop on the vision control loop provides several advantages according to hybrid- and impedance-based vision/force control. For our experiments, we consider a system consisting of a camera and a force sensor mounted on the end-effector of a manipulator (see Figure 1). The task is to insert a peg in a hole by using vision and force feedback simultaneously.

In Section 2, an overview of visual servoing techniques is presented and the need for vision/force coupling is justified. In Section 3, the existing approaches for vision/force control are analyzed and simulation results are presented showing their main drawbacks. The proposed scheme is described in Section 4 along with some simulation results in the cases where the others fail.

II. VISUAL SERVOING

Motivated by the desire to reduce or avoid the need for environmental modeling, the use of visual observations to control robot motion has been extensively studied in the last years. Typical applications of visual servoing methods are the positioning of a robot and the tracking of objects using visual information provided by an in-hand camera.

A. Control law

Several vision-based control laws have been proposed in the literature [8]. They are generally classified in three groups, namely position-based, image-based and hybrid-based control. The first one, based on the computation of a 3-D Cartesian pose, requires most often a CAD-model of the object and a calibrated camera [12]. Contrarily to classical position-based approach, imagebased visual servoing does not need a full model of the target. In this second approach, the control loop is directly closed in the image space [6]. As a consequence robustness to modeling errors and noise perturbations is increased with respect to position-based approaches [3]. More recently, several researchers have explored hybrid approaches which combine Euclidean and image information in order to design globally stabilizing control [4], [11].

Consider the vector $\mathbf{s} = (\mathbf{s_1}^T, \mathbf{s_2}^T, \cdots \mathbf{s_n}^T)^T$, where $\mathbf{s_i}$ is a m-dimensional vector containing the visual observations used as input of the control scheme. If the 3D features corresponding to visual observations are motionless, the time derivative of $\mathbf{s_i}$ is:

$$\dot{\mathbf{s_i}} = \frac{\partial \mathbf{s}_i}{\partial \mathbf{X}} \frac{d\mathbf{X}}{dt} = \mathbf{L}_i \tau$$

where τ is a 6-dimensional vector denoting the velocity of camera and containing the instantaneous angular velocity $\boldsymbol{\omega}$ and the instantaneous linear velocity $\mathbf{v}$ of a given point expressed in the image frame. The $m \times 6$ matrix $\mathbf{L}_i$ is the interaction matrix. It links the variation of the visual observations to the camera velocity. If we consider the time derivative of $\mathbf{s}$, the corresponding interaction matrix is $\mathbf{L} = (\mathbf{L}_i, \cdots, \mathbf{L}_n)^T$ and $\dot{\mathbf{s}} = \mathbf{L} \cdot \tau$. To design the control law, we use the task function approach introduced by Samson et *al* in [20]. Consider the following task function $\mathbf{e}$ to be regulated to $\mathbf{0}$:

$$\mathbf{e} = \widehat{\mathbf{L}}^+(\mathbf{s} - \mathbf{s}^*)$$

where $\mathbf{s}^*$ is the desired value of the observation vector $\mathbf{s}$ and $\widehat{\mathbf{L}}^+$ is the pseudo-inverse of a chosen model of $\mathbf{L}$. The expression of $\mathbf{L}$ can be found in [6] for different sort of image features. The time derivative of the task function is:

$$\dot{\mathbf{e}} = \frac{d\widehat{\mathbf{L}}^+}{dt}(\mathbf{s} - \mathbf{s}^*) + \widehat{\mathbf{L}}^+\dot{\mathbf{s}} = (\mathbf{O}(\mathbf{s} - \mathbf{s}^*) + \widehat{\mathbf{L}}^+\mathbf{L})\tau$$

$\mathbf{O}(\mathbf{s}-\mathbf{s}^*)$ is a 6-dimensional square matrix such that $(\mathbf{O}(\mathbf{s}-\mathbf{s}^*)|_{\mathbf{s}=\mathbf{s}^*} = \mathbf{0}$ If we consider the following control law:

$$\tau = -\lambda \mathbf{e} = -\lambda \widehat{\mathbf{L}}^+(\mathbf{s} - \mathbf{s}^*) \qquad (1)$$

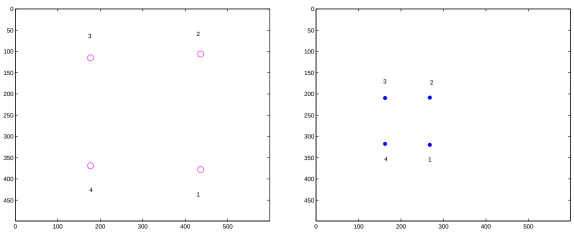
then the closed-loop system is $\dot{\mathbf{e}} = -\lambda(\mathbf{O}(\mathbf{s}-\mathbf{s}^*)+\widehat{\mathbf{L}}^+\mathbf{L})\mathbf{e}$. It is well know that such system is locally asymptotically stable in a neighborhood of $\mathbf{s}^*$ if and only if $\widehat{\mathbf{L}}^+\mathbf{L}$ is a positive defined matrix. In order to compute the control law (1) it is necessary to provide an approximated interaction matrix $\widehat{\mathbf{L}}$.

B. Considered task

For the scope of this paper, we consider a peg-in-hole task, where a robot with an eye-in-hand camera has to insert a peg of 10 cm length into a hole of the same depth. The difference between the peg and the hole diameters is 3 mm. The hole is in the center of a pattern composed by four circles forming a square, as shown in Figure 1. We assume that the hole, and thus also the pattern, are on the origin of the world frame, but rotated 10 degrees around Y axis (one of the axis contained in the pattern plane).

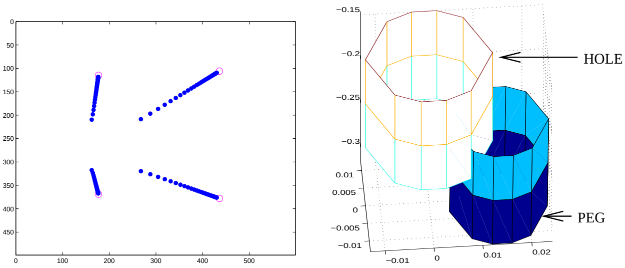
The goal of the vision part is to reach a camera position so that the square is centered on the image at a given size (see Figure 2a). This desired position corresponds to the one when the peg is successfully inserted into the hole, and can be learnt during an off-line process. Figure 2 shows an example of image-based visual servoing for reaching the desired features position, starting from a set of initial features that are taken from the initial cartesian position $\mathbf{X} = (0.08, -0.02, -0.6, 0, 0, 0)^T$ (units in meters and degrees) with respect to the world reference frame.

By the control law of equation 1, and properly taking the interaction matrix $\mathbf{L}$ for the four point features, we can see in



(a) (b)

Fig. 2. Image-based visual servoing: (a) Desired image, (b) initial image



(a) (b)

Fig. 3. First simulation with vision controller only: (a) Trajectories in the image plane, (c) Collision between peg and hole

Figure 3a how the system converges to the desired position. However, as it can be seen in Figure 3b, during the trajectory from the initial to the desired position, the peg collides with the surface that contains the hole. Thus, in real life, both the robot and the environment could be damaged. It is for this reason that, for tasks that involve interaction with the environment, it is necessary to complement the vision control loop with force feedback, taking into account the task forces.

III. Classical vision/force coupling approaches

In order to cope with task forces while performing visual servoing, vision/force coupling schemes have been proposed in the literature. Our goal is not to describe the field of vision/force control but to show with representative examples the general structure of actual schemes and therefore to prove the originality of the new approach described in the next section. We first present hybrid-based approach and then we focus on impedance-based approach.

A. Hybrid based vision-force control

Several hybrid vision/force control schemes have been proposed and applied [16], [15]. They are all following the architecture shown in Figure 4, which is equivalent to hybrid position/force control [9]. The input to the vision control law (VCL) is computed from desired and current visual features, $\mathbf{s}^d$ and $\mathbf{s}$. In this approach, it is necessary to ensure orthogonality between vision and force controller outputs τ_v and τ_f to avoid any conflict at the actuator level. Hybrid control separates vision control and force control into two separate control loops, that operate in orthogonal directions, as shown in Figure 4. A diagonal selection matrix $\mathbf{S}$ and its complementary $\mathbf{I}-\mathbf{S}$ are introduced into control chains.

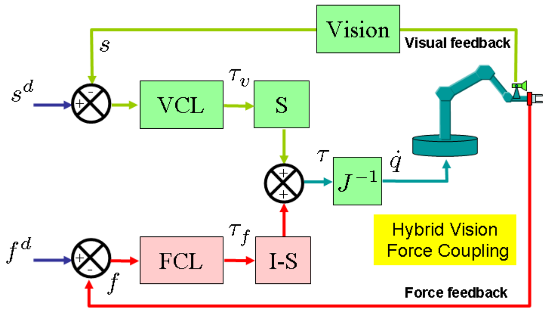


Fig. 4. Hybrid vision/force scheme

The diagonal matrices are applied to vision and force errors defined in a constraint frame on the task space. In order to produce a resulting motion, vision and force contributions are combined in the following way:

$$\tau = \mathbf{S}\tau_v + (\mathbf{I}-\mathbf{S})\tau_f \tag{2}$$

where τ_v is the output of the vision control law (VCL) according to equation (1) (taking $\mathbf{s}^* = \mathbf{s}^d$), and τ_f is the output of the force control law (FCL) taking into account the desired behavior of the system according to the relationship between force and differential displacement by means of the stiffness matrix ($\mathbf{f} = \mathbf{K}\cdot d\mathbf{X}$; $\dot{\mathbf{X}} = \mathbf{L}_X \cdot \tau_f$, being $\mathbf{L}_X$ the interaction matrix corresponding to the 3D pose definition X).

Hybrid control allows visual servoing only in those directions that are orthogonal to directions along which force feedback is used. If a force perturbation occurs in the force controlled direction the positioning error generated can not be corrected by the vision-based controller.

This is shown by simulation in Figures 5 and 6. For this experiment, a hybrid control law has been implemented. The selection matrix is chosen to be the identity matrix when there is no contact. Once contact is detected, the selection matrix is set to $\mathbf{S} = \mathbf{diag}(1,1,0,0,0,1)$ according to the task to perform. By setting an initial cartesian position $\mathbf{X} = (0.02, -0.02, -0.36, -5, 5, 0)^T$ expressed in the world frame, the corresponding initial image features are shown in Figure 5b. Figures 6a and 6b show how the desired image position is never reached, and so, the image error does not converge to zero. This happens because this control law relies entirely on the selection matrix, which is task-dependent, and only has meaning when the tool frame is aligned with the constraint frame where $\mathbf{S}$ has been defined. For our chosen initial position, both frames are not aligned. The control law starts to converge as long as no contact is detected (see the dynamic and kinematic screw on the very first iterations in Figures 6c and 6d), because in this case all degrees of freedom are vision-controlled. The first contact appears on the surface than contains the hole, before the peg is completely aligned with it. Some degrees of freedom switch to force-control, and thus the vision error on these directions is not corrected

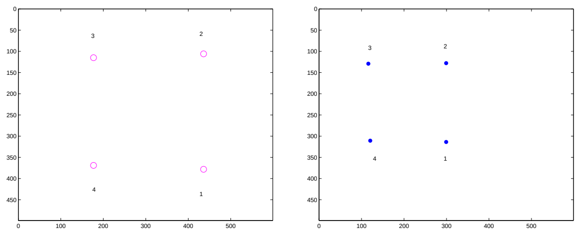

(a) (b)

Fig. 5. Hybrid vision/force: (a) Desired image, (b) initial image

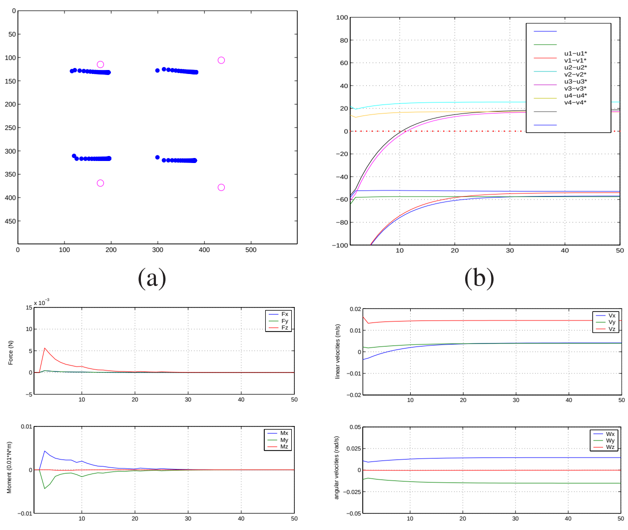

(a) (b)
(c) (d)

Fig. 6. Hybrid vision/force: (a) Features Trajectory in the image plane, (b) image error, (c) dynamic screw, (d) kinematic screw

In conclusion, the hybrid-based vision/force control is only valid when the task is perfectly known and the tool frame is well-aligned with the constraint frame. If contacts appear before vision has converged, then the desired position may not be reached.

B. Impedance based vision-force control

Impedance position/force control framework allows to a priori define the way the manipulator shall react with respect to external force disturbance. Using such a scheme, the six degrees of freedom can be simultaneously position- and force-controlled. A programmable mechanical impedance $\mathbf{Z}$ is thus provided to the end-effector [9]:

$$\mathbf{F}(p) = p\mathbf{Z}(p)\mathbf{X}(p) \tag{3}$$

The robot is supposed to be equivalent to a mass-spring-damper second-order system whose transfer function is:

$$p\mathbf{Z}(p) = \Lambda p^2 + \mathbf{B}p + \mathbf{K} \tag{4}$$

where Λ, $\mathbf{B}$ and $\mathbf{K}$ are respectively the desired inertia, damping and stiffness matrices. By considering only the damping matrix, the mechanical impedance becomes $\mathbf{Z}(p) = \mathbf{B}$. For vision/force impedance control (see Figure 7), the final control vector can be written as $\tau = \tau_v + \tau_f$, where τ_v is the kinematic screw computed by the vision control law, and τ_f is computed by the force control loop. Thus, the expression for impedance vision/force control can be written as:

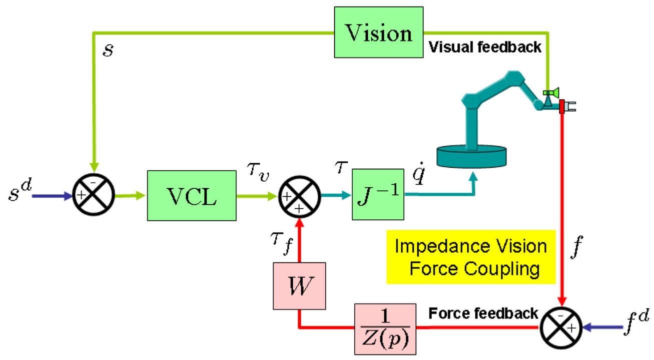


Fig. 7. Impedance based vision/force control scheme

$$\tau = -\lambda \mathbf{L}^+(\mathbf{s} - \mathbf{s}^d) + \mathbf{W}\mathbf{B}^{-1}(\mathbf{f}^d - \mathbf{f}) \tag{5}$$

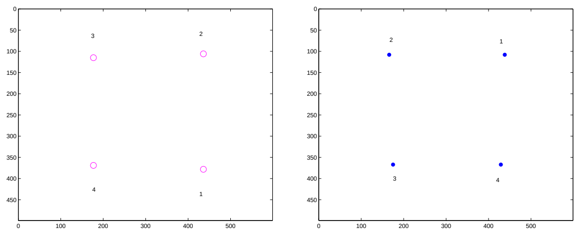
where $\mathbf{W} = \mathbf{L}_X^{-1}$ so that $\tau_f = \mathbf{W} \cdot \dot{\mathbf{X}}$.

With such a serial scheme, it is possible that $\mathbf{s} \neq \mathbf{s}^d$ and $\mathbf{f} \neq \mathbf{f}^d$ while $\tau = 0$. A local minima can thus be attained and oscillatory phenomena can occur.

This is shown by simulation in Figures 8 and 9. Figure 8b shows the camera image when the robot is the initial cartesian position $X = (0, 0, -0.25, 0, 0, 90)$ with respect to world frame. We can see in Figures 9a and 9b how the system starts to converge, but, finally, the desired position is never reached. We can also see in Figures 9c and 9d an oscillatory behavior of the dynamic and kinematic screw. This is because the control law has reached a local minima. The vision control law computes a kinematic screw for reducing the image error, but it is opposite to the dynamic screw computed by the force control law. As coupling is done in cartesian space, the result is that the robot is continuously oscillating between the direction that reduces the vision error and the one that reduces force error.

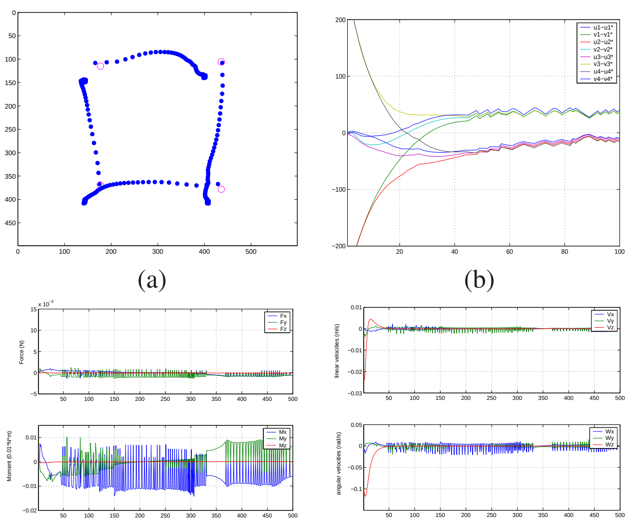
C. Discussion

We have analyzed the existing methods for vision/force control and have shown their main drawbacks by simulation results. Hybrid vision/force control is unable to control all the degrees of freedom in vision and force simultaneously. This leads to some cases where convergence is not possible. Regarding impedance vision/force control, the coupling between the vision and the force control laws is done in cartesian space. A local minima can be reached during convergence making it impossible to simultaneously reach the desired force and vision references. In the next section, we will present a new approach for vision/force control that solves these problems: the external hybrid structure for the force-vision control, where the force control loop is no longer parallel, but external, to the vision control loop. Thus, coupling is not done in cartesian space, but in sensor space,



(a) (b)

Fig. 8. Impedance vision/force: (a) Desired image, (b) Initial image



(a) (b) (c) (d)

Fig. 9. Impedance vision/force: (a) Features Trajectory in the image plane, (b) image error, (c) dynamic screw, (d) kinematic screw

so that any conflict between vision and force control laws can be avoided.

IV. External hybrid vision-force control

A. General concept

In our approach, the force control loop is closed around an internal vision control loop in a hierarchical way (see Figure 10). The reference trajectory $\mathbf{s}^d$ used as input of the vision-based controller is modified according to the external force control loop. The force control is performed by direct control: when the robot is moving from $\mathbf{dX}$ against a contact surface, the force measurement is proportional to the environment stiffness $\mathbf{K}$ and the displacement $\mathbf{dX}$. The desired vector of image observation $\mathbf{s}^d$ is then modified according to the force controller output, which is a relative position $\mathrm{d}\mathbf{X}$, projected on sensor space by means of the interaction matrix $\mathbf{L}$. When the end-effector is not in contact with external environment, the output of the force controller is null and the robot is controlled according to the vision-based controller output. Otherwise the force controller only modifies the reference trajectory of visual observations.

B. The proposed control law

In the control scheme, shown in Figure 10, the desired wrench $\mathbf{f}^d$ is added as input in the force feedback control

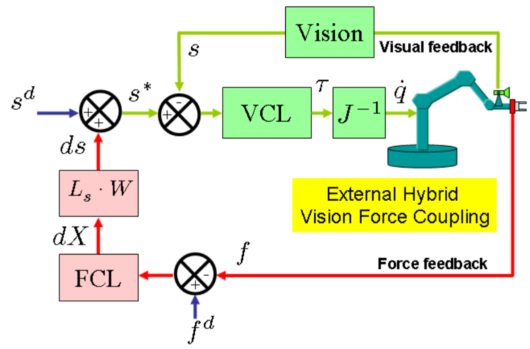


Fig. 10. External hybrid vision/force control loop

loop. Note that this has no effect on closed loop behavior, since the wrench input can be viewed as a reference trajectory modifier [14]. The stiffness is controlled by the force controller (FCL) according to a proportional control law:

$$d\mathbf{X} = \mathbf{K}^{-1}(\mathbf{f}^d - \mathbf{f}) \tag{6}$$

The force controller only modifies the reference trajectory of visual observations $\mathbf{s}^d$:

$$\mathbf{s}^* = \mathbf{s}^d + d\mathbf{s} \tag{7}$$

where $\mathbf{s}^*$ is the modified reference trajectory of image features and $d\mathbf{s}$ can be computed by projecting $d\mathbf{X}$ by means of the interaction matrix as $d\mathbf{s} = \mathbf{LW}d\mathbf{X}$ (note that $d\mathbf{s}$ can also be computed using the camera and object models if they are available).

C. Simulation results

Figures 11 and 12 show how the external hybrid control behaves in the examples where the hybrid-based and impedance-based control fail. As we can see, the external control converges without problems in both cases.

For the first example, as we can see in Figures 11c and 11d, there is a force in Z direction (approaching direction) that corresponds to the contact with the surface before inserting the peg. The velocity becomes zero in this direction, but not in the others, meaning that, even in the presence of contact, vision is converging in the non-constrained directions. During this stage, the peg is in contact with the external surface, moving in tangent directions until the hole is found (thanks to the vision convergence). At this point, the force in Z disappears and the peg is inserted successfully.

In the second example, where impedance-based control fails, the external approach succeeds, because it avoids the conflict between vision and force control laws by hierarchically putting the force loop around the vision loop. The coupling is thus done in sensor space, and the control law that finally acts on the robot is only the vision one, thus avoiding local minima. Figure 12c shows that some torques appear during the execution of the task. These torques temporarily modify the vision reference and, thus,

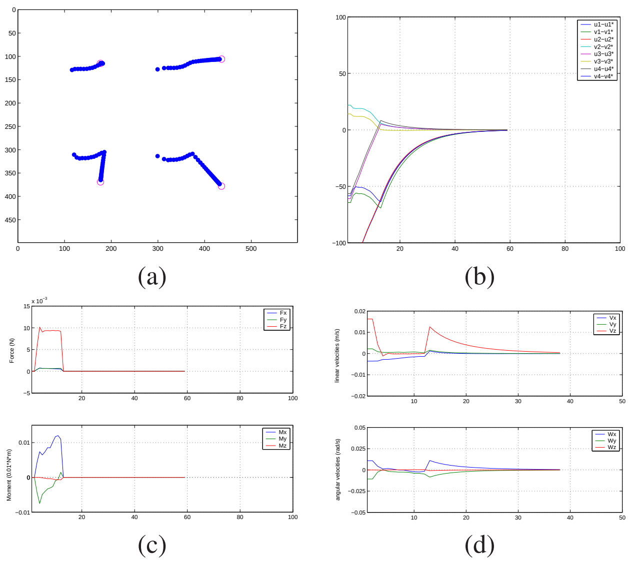


Fig. 11. External hybrid vs. Hybrid-based: (a) Features Trajectory in the image plane, (b) image error, (c) dynamic screw, (d) kinematic screw

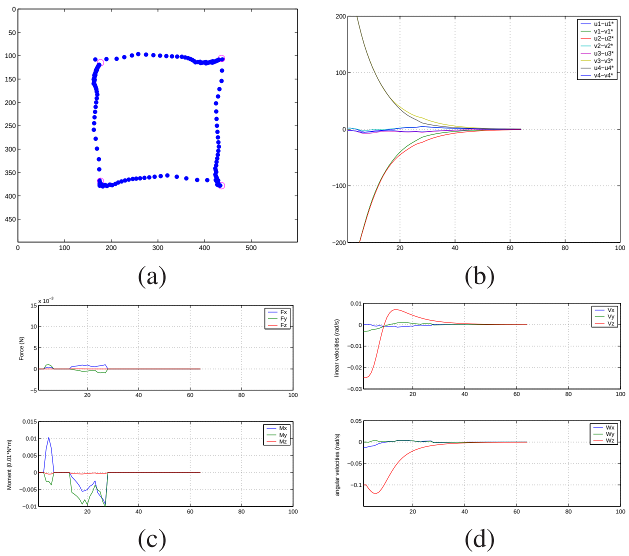


Fig. 12. External hybrid vs. Impedance-based: (a) Features Trajectory in the image plane, (b) image error, (c) dynamic screw, (d) kinematic screw

the vision control law computes a control vector that helps the convergence of both vision and force.

V. Conclusion

For tasks that involve interaction with the environment, it is necessary to complement the vision control loop with force feedback by means of a vision/force control law. Previous work has been based on hybrid and impedance vision/force control, but, as we have shown in this paper, both methods present problems that may affect the convergence. We have proposed a new scheme for a hybrid force/vision control based on the concept of external control. The hierarchical juxtaposition of the force control loop on the vision control loop provides several advantages according to the existing methods: selection matrices and time-dependent geometric transformations are eliminated from the control loop leading to a controller design independent of the arm configuration. Since the force control only acts on the reference trajectory, conflicts between force and vision controller are avoided. Our aim is to validate experimentally our approach in comparison with the existing methods, and to make further research in order to extend it so that robot dynamics are also taken into account.

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