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Integrating Path Planning and Visual Servoing in Manipulation Tasks

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Abstract—This paper proposes a novel methodology to integrate both geometric manipulation planning and visual servoing. Geometric manipulation planning is able to handle robots with many degrees of freedom in cluttered environments while visual servoing makes execution of the planned trajectories robust to inaccuracies. The method is illustrated by a demonstration on a real humanoid robot manipulating an object.

I. INTRODUCTION

Performing manipulation tasks including regrasping on a humanoid robot is known to be a difficult task for several reasons. The first reason is the necessity for the robot to measure the position of the objects to manipulate with on-board sensors, before grasping but also after each grasp or regrasp since the object may slightly slide in the gripper during those steps. This perception issue is far from being solved for any object. The second reason resides in the high number of degrees of freedom of the system (robot + objects) and in the complexity of manipulation planning in the presence of obstacles.

To cope with the first reason mentioned above, a lot of work has been proposed in visual servoing in order to control the motion of the robot based on the perception of the position of the objects that are to be manipulated.

To cope with the second reason, a lot of work has also been proposed to plan manipulation motions based on models of the robot, of the objects and of the obstacles.

To our knowledge however these two corpuses of work have largely evolved independently. Visual servoing usually aims at reducing an error between perceived and desired features. It does not take into account the reference trajectory that may have been planned priorly by a motion planner. One may argue that the planned trajectory implicitly defines a time-parameterized trajectory for the desired feature to be controlled by visual servoing, as in [15]. However, if the feature image is affected only by a subset of the robot degrees of freedom – the left arm for instance, the other degrees of freedom will not be controlled.

A. Visual servoing

[3], [4] provide an overview of the state of the art in this domain until 2007. The second reference mentions the case of moving target only at the very end. In a more recent work [2], the authors perform a grasp task on a Romeo humanoid robot, tracking the position of the hand and of the object to grasp with a camera. In this latter work, there are no obstacles and collision of the hand with the object during the approach phase is not addressed.

B. Manipulation planning

Manipulation planning is a class of path planning problems where some robots manipulate some objects with grippers, in an environment cluttered with obstacles. Manipulation constraints raised by the fact that objects cannot move if they are not grasped and that they are rigidly attached to a gripper when they are grasped define several foliations of the configuration space of the whole system (robots + objects). From a given configuration with a given set of grasps, the system can only move on a submanifold of the configuration space called a leaf.

Since the pioneering paper [24], manipulation planning has been tackled using random sampling based method [10], [12] in order to explore the leaves of those foliations [21]. Manipulation planning is traditionally decomposed into several subdomains: Rearrangement planning [11], [20], [13], [6] where the goal specifies only the final position of the objects, multi-arm motion planning [8], [9], [5], and navigation among movable obstacles.

C. Sensor-based manipulation planning and control

[25] addresses the problem of rearrangement planning for a disc robot manipulating circular objects in the plane. The paper presents impressive experimental results with a quadruped robot equipped with a lidar and avoiding...
unexpected obstacles. [22] proposes a method to plan a sequence of controllers that move a system composed of two robots and one object from an initial state to a goal state in a dynamic environment. The algorithm performs a random exploration of the configuration space, using simulated controllers as a steering method. The controllers are implemented using eTaSL/eTC framework [1]. Our work share similarities with this latter paper. The main differences are that we do not explicitly address dynamic environments, but we implement visual servoing.

D. Contribution

In this paper, we propose a novel approach to manipulation planning and control for a robot with a high number of degrees of freedom in the presence of obstacles. The approach is broken down into three steps. In the first step, a manipulation planning algorithm computes a manipulation planning path starting from the initial configuration and reaching a goal configuration or set of configurations. In the second step, the manipulation path is decomposed into segments. To each segment a controller taking into account both the planned path and visual features attached to objects or robot bodies is associated. These controllers regulate sequences of tasks with priority orders [23]. In the third step, a finite state machine keeps track of the current segment and selects the controller accordingly. Note that a preliminary version of this work has been described in [19]. However, in this previous work, no visual servoing was implemented.

The paper is organized as follows. In Section II, we define the problem and introduce some notation. In Section III, we describe the manipulation planning algorithm that we use to produce reference trajectories. In Section IV, we explain how a manipulation trajectory is mapped to a sequence of hierarchical task based controllers. In Section V, we describe how the resulting motion is executed by the robot. In Section VI, we describe some experimental results that validate the approach.

II. DEFINITION OF THE PROBLEM

We consider a robot with configuration space denoted as $C_r$ and $n_o \geq 1$ objects of configuration spaces $SE(3)^n$. The configuration space of the whole system is the Cartesian product of the configuration spaces of the robot and objects: $C = C_r \times SE(3)^{n_o}$. Some static obstacles are present in the workspace of the robot.

A. Grippers, handles, grasps

The robot is equipped with $n_g \geq 1$ grippers i.e. frames that are attached to some of its links. To each object $o_i$, $i \in \{1, \cdots, n_o\}$, $n_{h,i} \geq 0$ frames called handles are rigidly attached. We denote by

- $g_1, \cdots, g_{n_g}$ the robot grippers,
- $h_{j,i}$ for $i \in \{1, \cdots, n_o\}$ and $j \in \{1, \cdots, n_{h,i}\}$ the $j$-th handle of $o_i$.

For any configuration $q \in C$, and any gripper $g$ and handle $h$, we denote by $g(q) \in SE(3)$ and $h(q) \in SE(3)$ the positions of $g$ and $h$ in configuration $q$. We define a grasp – denoted as $gr(g,h)$ – as the part of $C$ containing all configurations of the system such that the frames defined by $g$ and $h$ are at the same position:

$$gr(g,h) = \{q \in C, g(q) = h(q)\}.$$

B. Contact surfaces, placements

To each object $o_i$, $i \in \{1, \cdots, n_o\}$, $n_{c,i} \geq 0$ convex polygons called object contact surfaces are rigidly attached. Convex polygons called environment contact surfaces are attached to the environment.

- Contact surfaces of $o_i$ are denoted by $c_{i,j}$ for $j \in \{1, \cdots, n_{c,i}\}$.
- Environment contact surfaces are denoted by $c_{0,j}$, for $j \in \{1, \cdots, n_{c,0}\}$.

An object is in a placement configuration if one of its contact surfaces is in contact with one environment contact surface. Two convex polygons are said to be in contact if the plane containing one is inside the other.

C. Visual features

The robot is equipped with a RGB-D camera providing an image $I \in RGBD = Co \times Co \times Co \times \mathbb{R}$ where $Co \triangleq \{0, \cdots, 255\}$. We assume that a localization function is able to localize object $o_i$ with $i \in \{1, \cdots, n_o\}$ or gripper $g_j$ with $j \in \{1, \cdots, n_g\}$ such that:

$$^cT_{o_i} : I_{o_i} \mapsto SE(3)$$

$$^cT_{g_j} : I_{g_j} \mapsto SE(3)$$

where $I_{o_i} \subset RGBD$ and $I_{g_j} \subset RGBD$ are the domains of the image space where the localization function successfully computes a pose, $^cT_{o_i}$, $^cT_{g_j}$ are the respective poses of $g_j$ and $o_i$ in the camera frame, as computed by the localization function. We denote by

$$g_jT_{o_i} = ^cT_{g_j}^{-1} ^cT_{o_i} : I_{o_i} \cap I_{g_j} \mapsto SE(3)$$

the localization function that maps an image to the relative pose of the object in the gripper frame.

D. Problem definition

The problem we want to solve consists in moving the system from an initial configuration where the objects are in stable configurations, to a goal configuration where the objects are still in stable configurations. We decompose this problem in a sequence of sub-problems:

1) manipulation planning: computation of a collision-free manipulation path along which each object is either in a stable configuration or grasped by a gripper,
2) controller generation: computation of a sequence of controllers corresponding to successive segments of the planned path.

3) motion execution: successive activation of each controller after detection of the end of the previous segment.

Item 2) above is the main contribution of this paper. In the three following sections, we explain how we tackle the above sub-problems.

III. MANIPULATION PLANNING

To plan a manipulation path, we use algorithm Manipulation RRT as described in [16]. This algorithm is an extension of RRT that explores the foliations induced by the manipulation constraints.

A. Constraint graph

The manipulation constraints are stored in a graph

- the nodes of which are sets of grasps as defined in Section II-A called states, and
- the edges of which are called transitions and connect states that differ by only one grasp.

Transitions contain the constraints of the state they belong to and additional constraints stating that objects not grasped should not move. See Figure 2 for an example.

B. Grasp waypoints

Grasp configurations are usually very close to collision since the object and gripper are almost in contact. To avoid the so called narrow passage effect in path planning, we define some intermediate states called waypoints in the constraint graph. clearance parameters are added in the model of each object handle and of each robot gripper. For each pair \((g, h)\) of gripper and handle, the pregrasp of \(h\) by \(g\) is defined as the following subset of \(C\)

\[\{q \in C, \; g(q)^{-1}h(q) = T\},\]

where

- \(g(q)^{-1}h(q) \in SE(3)\) is the relative position of \(h\) in \(g\) frame (in configuration \(q\),

Fig. 2. Constraint graph corresponding to a robot with one gripper and one object with one handle. "\(g > h\)" (resp. "\(g < h\)"") in transition names means that grasp of \(h\) by \(g\) is created (resp. removed). "\(|s|\)" means that transition starts from state \(s\). Note that transition "\(g_1 > h_1,1|pl(o_1)\)" lies in state \(pl(o_1)\) and therefore contains the constraint that the object should be in a stable position. It also contains an additional constraint stating that the object should not move along this transition.

Fig. 3. Top: partial view of a constraint graph with a grasp waypoint state inserted between two states. The robot has two grippers \(g_1, g_2\) and manipulates object 1 by two handles \(h_{1,1}, h_{1,2}\). Bottom: example of a configuration in waypoint state \(g_2 > h_{2,1}|gr(g_1, h_{1,1})|pg\). \(cl_o\) and \(cl_1\) respectively represent the clearance of \(h_{1,2}\) and of \(g_2\). Red arrows represent \(x\)-axes.

Fig. 4. Top: partial view of a constraint graph with 3 placement waypoint states inserted between two states. Bottom: example of 3 configurations in waypoint states pregrasp (pg), grasp-placement (gp) and preplacement (pp).
• $T \in SE(3)$ is the translation along $x$ axis of abscissa
  the sum of gripper and handle clearances.

With this definition, we augment the constraint graph with
intermediate pregrasp states along transitions that create a
new grasp. See figure 3 for an example.

C. Placement waypoints

Between a state where an object is in placement and a
state where the same object is grasped – all other grasps
and placement being unchanged, we insert 3 waypoint states

• pregrasp: defined as in the previous section [III-B],
• grasp-placement: the object is grasped and still in
placement,
• preplacement: the object is grasped and translated by a
positive distance equal to the grasp clearance along the
normal to the environment contact surface.

D. Special transitions

Using definitions in sections [III-B] and [III-C] for clarity,
we refer to some transitions as follows.
• Grasp transitions connect pregrasp and grasp-placement
states.
• Release transitions connect grasp-placement and pregrasp
states.
• Lift transitions connect grasp-placement and preplacement
states.
• Put transitions connect preplacement and grasp-placement
states.
• Loop transitions connect a state to itself.

In the above definitions, we do not make any difference
between waypoint and regular states. Figures 3 and 4 show
examples of these transitions.

E. State pruning

Without additional information, each gripper may grasp
each handle, making the number of states potentially very
high. To keep the number of states reasonable, we filter out
states that are empty because

1) configurations satisfying the grasp constraints of the
state are always in collision, or
2) no configuration satisfies the grasp constraints of the
state.

States of the first type are detected by randomly generating
one configuration in the state and by testing collision only
of the bodies constituting the grippers. Those body relative
positions are indeed constant for all configurations of the
state. States are declared of the second type if none of
a given number of attempts to generate a configuration in
those states is successful. Attempting to generate a node in
a state consists in generating a random configuration and to
solve the state constraints using a Newton based non-linear
equation solver as described in [18] (Algo 1).

F. Path smoothing

The result of Manipulation RRT is post-processed in two
successive steps in order to make it executable on a real
robot.

1) a random shortcut algorithm is applied [7] to shorten
the path and remove useless detours,
2) the result of the previous step is time-parameterized
using sequences of Bezier curves in order to make it
continuously differentiable and in order to bound the
maximal joint accelerations from above.

IV. Sensor based motion control

The output of the manipulation planning process described
in the previous section is a continuously differentiable tra-
jectory composed of a sequence of segments such that
each segment is subject to a set of numerical constraints
stored in the constraint graph edges. Segments are linked
by configurations that belong to states (including waypoint
states) of the constraint graph.

If models of the robot, of the object and of the environment
were perfect, if the control of the robot motors were perfect
and if the sensors were perfect, controlling the joints by
feeding them with the planned trajectory would make the
task execution successful. However, in the real world, none
of the above is perfect. Particularly, if the robot links are
light as is the case for legged humanoid robots, the overall
flexibility of the structure induces important variations be-
tween the position of the end effectors computed via forward
kinematics and the actual position. Those variations can only
be partially corrected by a calibration step. In this paper, we
use visual servoing to cope with the above inaccuracies.

To do so, we use a hierarchical task-based controller as
described in [14]. This software basically implements the
algorithm described in [23].

A. Hierarchical task based controller

The controller is based on the following concepts:

• task: a mapping from $C$ to $T$ a vector space or a Lie-
group (usually $SE(3)$). It can represent the pose of an
end effector, the posture of the robot, the pose of an
object;
• task reference: a mapping from $R$ to $T$ that represents
the desired trajectory of the task along time.
• error: a mapping from $T \times T$ to a vector space that maps
to zero pairs of identical task values. For instance, if the
task is the pose ($T = SE(3)$) of a robot end effector,
and if $T_1$, $T_2$ are two elements of $SE(3)$,

$$e_{SE(3)}(T_1,T_2) = \log(T_1^{-1}T_2)$$

(3)

is the screw velocity $\langle v, \omega \rangle \in R^6$ that moves $T_1$ to $T_2$
in unit time. Particularly, the error is equal to zero iff
$T_1 = T_2$. If $T = R^n$ for a given positive integer $n$,

$$e_{R^n}(T_1,T_2) = T_2 - T_1.$$  

(4)

Note that expression (3) is equivalent to (4) if we
consider $R^n$ as a Lie group with $+$ operator.
If we consider a planned trajectory $\Gamma$ as a mapping from $\mathbb{R}$ to $C$, and a task $T$ with output space $T$, we define the task reference associated to $T$ for the trajectory $\Gamma$ as the mapping from $\mathbb{R}$ to $T$:

$$T^*(t) \triangleq T(\Gamma(t))$$

and the error for this task along $\Gamma$ as the mapping from $C \times \mathbb{R}$ to $\mathbb{R}^n$ for a given $n$:

$$e(q, t) \triangleq e_T(T(q), T^*(t)).$$

A hierarchical task based controller is initialized with an ordered list of tasks $T_i$, $i \in \{1, \cdots, m\}$ for some positive integer $m$, with decreasing order of priority. It takes as input a robot configuration $q$ and computes a robot control $\dot{q}$ in order to make the errors converge to 0. If no value of $\dot{q}$ makes all the errors converge to 0, the controller computes the best control value $\dot{q}$ given the priority order. We refer to [14] for details about the computations.

### B. Synthesis of a sequence of controllers

The main contribution of this paper is the automatic generation of a sequence of hierarchical task-based controllers, one for each transition of the constraint graph along a planned trajectory. To each type of transitions defined in Section III we associate a controller as described below.

- **a) System specific task:** Possible robot specific constraints are inserted at the higher priority level (level 1). This task can be for instance quasi-static equilibrium of a legged humanoid robot, or a predefined trajectory of the base of a mobile manipulator. Note that these constraints are also used during motion planning.

- **b) Posture task:** The posture task takes values in $\mathbb{R}^n$ where $n$ is the number of actuated degrees of freedom of the robot. The value of the task for a given configuration $q$ is obtained by extracting from $q$ the parameters corresponding to the actuated degrees of freedom.

  Tasks specific to each transition are inserted between the system specific task and the posture task as described in Figure 6.

  - **c) Visual servoing task:** In this task, the relative pose of object $i$ in the robot gripper $g_j$ frame is regulated. Therefore the task output is $T_{g_j}^{-1}T_{o_i}$, where $T_{g_j}$ and $T_{o_i}$ are the respective poses of $g_j$ and $o_i$.

  - **d) Grasp and release transitions:** if the link of the robot about to grasp the object to be grasped is equipped with a visual feature, the transition specific task is a visual servoing task of output space $SE(3)$. The value of the task is the relative pose of the object in the gripper frame.

  - **e) Put and Lift transitions:** if the object about to be put and the object (or environment) holding the contact surface are equipped with a visual feature, the transition specific task is a visual servoing task of output space $SE(3)$. The value of the task is the relative pose of the object in the frame of the contact surface.

  - **f) Loop transitions:** if along the transition, an object is grasped by two grippers, the transition specific task is the relative pose of a gripper with respect to the other one. This task value can be measured

    - by visual features if available, or
    - joint encoders and forward kinematics. In this case, the value of the task is the error computed from Equation (5), but the value measured by the joint encoders at the beginning of the transition.

  - **g) Other transitions:** transitions that do not fit one of the above definitions do not have any specific tasks.

  - **h) Note:** visual servoing tasks are inserted only if the corresponding visual features are visible from the robot.

Fig. 5. Sequence of controllers. As explained in Section III the output of the manipulation planning algorithm is a sequence of time-parameterized trajectory segments belonging to transitions of the constraint graph. In this figure, all states – waypoint or not – are represented by circles. Each trajectory segments belonging to transitions of the constraint graph.

Fig. 6. Controllers are associated to each type of transition.
camera. This can be enforced at the motion planning level by adding a constraint on the camera orientation, or at least predicted from the planned trajectory.

V. MOTION EXECUTION

Motion execution is performed on the robot using ROS architecture. The ROS nodes involved are displayed in Figure 7 and described below.

a) Vision: detects and publishes the poses of visual features with respect to the camera frame.

b) Estimation: reads the poses of objects as published by the Vision and the robot joint encoders. These raw data correspond to a configuration $q_\text{proj}$ that is not contained in any state of the constraint graph. The node projects $\hat{q}$ on all states and publishes the state and configuration $q_\text{proj}$ corresponding to the closest projection of $q$.

c) Planning: runs the manipulation planning algorithm and publishes the references that are extracted from the solution trajectory and that the controllers request. The initial configuration is read from the Estimation node.

d) Supervisor: computes the sequence of controllers and handles synchronisation between the different nodes.

e) Control: embeds the hierarchical task based controllers into the ros_control interface.

VI. EXPERIMENTAL RESULTS

We have implemented our framework on Pyrene robot displayed in Figure 1. The experimental setup is composed of the humanoid robot, a table and a wooden box both equipped with AprilTags [26].

In this section, we show the execution of a manipulation sequence where the robot is asked to flip a box upside down on a table. The reference path is planned and optimized by our software platform HPP as explained in section III.

VII. CONCLUSION AND PERSPECTIVES

This article proposes a new framework to automatize the bridge between motion planning and control. This is achieved by extracting in the planned trajectory the references that are relevant for a given portion of the trajectory. This article illustrates the application of this principle to visual servoing. Experimentations on Pyrene robot validate the effectiveness of the approach. They also point out some possible improvements for a future work. The first improvement would consist in growing obstacles and robot bodies for

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Fig. 8. Sequence of states visited to flip the box upside down. The robot grasps with one hand, changes hand and releases the object in a stable position. Red arrows correspond to visual servoing transitions. Note that visual servoing was not performed when changing hand since the required tags were not all in the field of view of the camera.
to better follow moving targets. Providing feedforward to the visual servoing tasks in order to manipulate planning to account for poor robot calibration. This operation would be performed only along transitions without visual servoing. The second one would consist in providing feedforward to the visual servoing tasks in order to better follow moving targets.

REFERENCES


