Motion planning with visual and tactile sensing for safety in uncertain environments

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***Abstract*—Most work in motion planning in uncertain domains focuses on a problem in which the robot has the ability to sense a sphere containing its body. But many robots do not have the ability to instantaneously sense in all directions and must, instead, move to gather information that guarantees they will be moving into unoccupied space. A robot with a pan-tilt head and a narrow field of view might need to deliberately look under a table before rolling its base underneath, for example. We have developed a strategy for planning trajectories, in arbitrary configuration spaces, that have the property that the robot does not move through any space without having observed it first. Although it was originally developed for robots with limited visual sensing, the techniques can be generalized to robots equipped with tactile sensors. The formulation we propose allows the robot to make unexpected contact with the environment, so long as contact is guaranteed to happen on specific contact-sensitive surfaces of the robot.**

I. Introduction

The motion planning problem traditionally achieves a certain notion of safety—no collision with obstacles that are known to the motion planner. In recent work, we describe an additional notion of safety that, given a specification of the region of workspace visible from a robot configuration (e.g. induced by the viewcone of a depth sensor and occlusions due to the robot and the environment), guarantees the robot will be positioned to detect any obstacle before it causes a collision. In this paper, we elaborate how our previous work can be applied to robots equipped with tactile sensors. We propose an extended model of safety that is appropriate for robots with both visual and tactile sensors. In the following, we begin by describing our approach to planning with incomplete information [1] and then discuss ways in which it can be directly applied to robots with tactile sensing.

II. Visibility-aware motion planning (VAMP)

A popular method for robot motion control is to assume a known map of the environment, and allow a motion planner to query the map via a collision checker. A correct motion planner will produce paths that are guaranteed to be collision-free with respect to the known obstacles. A common approach to handling unknown obstacles plans by optimistically assuming there are no unknown obstacles. If in the course of execution there are any observations that invalidate the plan, then the obstacle map is updated and a new plan is generated [2]. For this strategy to be correct, the motion planner must ensure that the robot is positioned so that it can perceive the relevant regions of the environment before it traverses them. Other work in navigating in uncertain environments typically assumes that the robot can observe the environment completely in its neighborhood e.g. at any vertex of a PRM the robot can observe whether all the incident edges are clear. In our previous work, we have focused on creating a planner that handles more restricted forms of visibility.

A. Formulation

Let W represent the (2- or 3-dimensional) workspace and C represent the configuration space for a robot. Let $W_{\text{obs}} \subseteq W$ represent the regions of workspace that are known to contain obstacles. At a configuration $q \in C$, the robot occupies some region of W, denoted by $S(q) \subseteq W$. We extend $S(q_i, q_j) \subseteq W$ to represent the swept volume of the robot moving from q_i to q_j, assuming e.g. linear motion in configuration space. The following constraint on a path $[q_1, \cdots, q_n]$ captures the notion of collision-free: $\forall i = 1 \cdots n-1 \; S(q_i, q_{i+1}) \nsubseteq W_{\text{obs}}$

To formulate the sensing, let $V(q, W_{\text{obs}}) \subseteq W$ represent the region of workspace visible from q. V takes into account self-occlusions and occlusions due to environment obstacles. For clarity, we may drop the W_{obs} argument. Let $v_0 \subseteq W$ be a region of workspace that has already been viewed and confirmed free (by default, it will be equal to $V(q_0)$, but for some robots it will need to be more, in order to allow any initial movement.) Let $v_i = v_0 \cup \bigcup_{j=1 \cdots i} V(q_j)$ be the region of space that has been seen by the robot after it has executed a path $[q_1 \cdots q_i]$ The visibility-safety constraint is

$$\forall i \; S(q_i, q_{i+1}) \subseteq v_i \tag{1}$$

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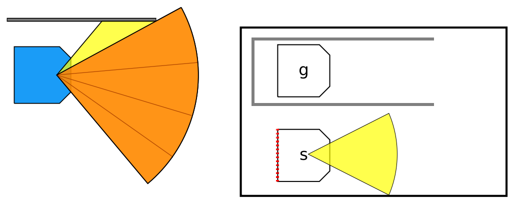
This formulation corresponds to a discrete-time model of vision, in which observations are not made during motion between configurations on the path.

B. Algorithm

Whereas the non-collision constraint in motion planning can be enforced pointwise at all configurations, the constraint of equation 1 depends on the path taken to a configuration. We have previously developed algorithms that can practically handle path-dependent constraints with visibility sensing. The key to this approach is that planned paths accumulate information about the environment. This framework can be applied to domains with tactile sensing as well, requiring only a different constraint.

III. Tactile sensing

If the robot is entirely covered in tactile sensors [3], then it could proceed without any special planning, assuming it is executing guarded moves (moving slowly enough to not



(a) (b)

Fig. 1: (a) Some possible sensed volumes with respect to robot configuration (blue) and environment (gray). The orange region can be covered with an unretractable cane. A few configurations of a cane are shown in black. The yellow region can be covered with a depth sensor (or retractable cane). (b) A robot with vision (yellow) and bump (red) sensing in a domain with start at s and goal at g.

damage itself before it can detect contact and halt). More generally, a robot cannot detect contact as it moves in an arbitrary direction in configuration space. We explore a few cases, starting with a case that reduces directly to the previous formulation of the VAMP problem. To handle more general robots, we require a new formulation of the safety constraint. Finally, we explain the strategies that a planner may exploit when a robot has access to both visual and tactile sensing modalities.

A. *Direct reduction to* VAMP *domains*

We consider a domain that resembles how a blind person sweeps a cane to detect obstacles, in which the previous formulation applies directly. We assume that the cane is permitted to contact the environment and reliably detects contact anywhere along its edge.

If the cane can be retracted radially, as well as be swept angularly, then the problem reduces to the domains where the depth sensor has a limited field of view and depth of view. If the cane cannot be retracted, the problem changes in two ways. 1. the function V behaves differently, since the "occlusions" induced by the known environment obstacles are larger, as shown in figure 1a. 2. the cane must be considered in the collision checking, and as such must be added to the planning state space. Even though the configuration of the cane is part of the state space, the planner itself does not need to plan the sweeping action, and does not need to consider every configuration of the cane. We may assume that the cane can be swept within the connected component of configuration space. More specifically, consider an equivalence class such that q_i and q_j are equal if the robot (ignoring the cane) is in the same pose but the cane itself is in different poses, and the cane may move freely from q_i to q_j. The planner may treat q_i to q_j as equivalent in most configurations, except for those that may transition into a configuration in which the configuration space becomes further disconnected.

B. *Extension of safety constraint*

The previous section demonstrates a specific robot for which tactile-safe motion planning reduces to a previous VAMP formulation. More generally, the robot may contain contact-sensitive and contact-insensitive surfaces. The planner would deploy the contact-sensitive surfaces, shielding the contact-insensitive surfaces and leading with the contact-sensitive ones. The tactile-equivalent of constraint 1 depends on the geometry of these surfaces. A motion is valid if the swept volume of the contact-insensitive surfaces does not include any unseen regions of workspace. To implement the check of the visibility-safety constraint 1, the robot geometry is discretized into points. This approximation enables handling the union without relying on explicit geometry calculations. It is similarly possible to formulate the tactile-safety constraint for point geometries.

C. *Visual and Tactile sensing*

A combination of vision and tactile sensors allow the option of moving quickly through known-free space and slowly, but leading with a contact sensitive surface in unknown space. To illustrate, consider a robot with a front-facing depth sensor and a rear bumper in figure 1b. The goal is still to move about safely in an uncertain environment. The planner decides when to do guarded moves (when it is relying on the tactile modality to guarantee safety), and when to move at full speed (when it is moving through space that has been previously seen or previously traversed). The structure of the VAMP algorithm remains the same, and a primitive motion is only valid if it satisfies equation 1, or if throughout the execution only contact-sensitive surfaces traverse unknown workspace regions. To achieve the goal, the planner for the robot in figure 1b may enter the hallway to visually confirm it is clear, then maneuver to the goal (which it cannot do directly, since the robot cannot turn inside of the narrow hallway), or it may execute a guarded move to back into the hallway, leading with the robot's contact-sensitive rear bumper.

IV. Conclusion

The VAMP problem is an interesting generalization of the traditional motion planning problem, with many possible extensions. This rich class of problems dealing with uncertainty are appealing because they are straightforward to formulate, yet admit many interesting solution strategies. We can extend this work to handle tactile sensors, so that the planner may position the robot's sensors in a deliberate way to enable the motion planning task to be achieved safely.

References

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