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Coordinating Robot Motion, Sensing, and Control in Plans

LDRD Project Final Report

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Coordinating Robot Motion, Sensing, and Control in Plans: LDRD Project Final Report

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Abstract

The goal of this project was to develop a framework for robotic planning and execution that provides a continuum of adaptability with respect to model incompleteness, model error, and sensing error. For example, dividing robot motion into gross-motion planning, fine-motion planning, and sensor-augmented control had yielded productive research and solutions to individual problems. Unfortunately, these techniques could only be combined by hand with ad hoc methods and were restricted to systems where all kinematics are completely modeled in planning. Our original intent was to develop methods for understanding and autonomously synthesizing plans that coordinate motion, sensing, and control.

The project considered this problem from several perspectives. Results included (1) theoretical methods to combine and extend gross-motion and fine-motion planning; (2) preliminary work in flexible-object manipulation and an implementable algorithm for planning shortest paths through obstacles for the free-end of an anchored cable; (3) development and implementation of a fast swept-body distance algorithm; and (4) integration of Sandia's C-Space Toolkit geometry engine and SANDROS motion planner and improvements, which yielded a system practical for everyday motion planning, with path-segment planning at interactive speeds. Results (3) and (4) have either led to follow-on work or are being used in current projects, and we believe that (2) will eventually be also.

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1 Introduction

At the time we proposed this project, autonomous motion planning largely divided into gross-motion planning, fine-motion planning, and sensor-augmented control.¹ Although this had yielded productive techniques, combining these techniques was done by hand and from scratch. Instead of a *continuum of adaptability* to errors in models, sensing, and control, we were left with (a) fragile gross-motion plans without provisions for any such errors and (b) relatively robust, sensor-utilizing fine motion plans that were limited to at most a couple of steps by the cost of planning. Furthermore, fine-motion plans were vulnerable to apparently minor qualitative model errors, such as an unmodeled screw head. Finally, most current notions of “motion plan repair” were either extremely limited (e.g., reactive collision avoidance) or abstracted away all geometry (various Artificial Intelligence approaches).

We proposed to develop methods for understanding and autonomously synthesizing plans that coordinate motion, sensing, and control. We hoped to develop generalized plans that would selectively retain the properties of gross- and fine-motion plans, and provide for run-time modification and repair, including necessary sensor-driven model updates. The final intent of the project was to be an implementation demonstrating these capabilities.

We first considered gross-motion and fine-motion planning theory. We investigated two basic questions: How can a gross-motion plan (GMP) or a fine-motion plan (FMP) be augmented so that execution-time system attempt to repair it reactively and decide to resume it? How should gross-motion planning and fine-motion planning be integrated into a single planner? In this vein, we (a) developed a framework that extends fine-motion plans with reactive plan repair; (b) studied an analogous approach for gross-motion plans; and (c) developed a method that combines fine- and gross-motion planning. In addition, mobile robot research by a supported graduate student at Cornell University provided a preliminary check of related ideas in a low dimensional domain.

Unfortunately, staffing problems made it difficult for us to continue work in the mobile robot area, and we judged the work outside the mobile robot domain to be limited in practicality. For this reason, we switched our focus to the manipulation of flexible objects. In this domain a low-dimensional configuration space [19] (C-space) cannot be used for exactly representing the state of the system or in exactly predicting its mechanics. We developed an implementable algorithm for planning shortest paths among obstacles for the free end of a planar cable anchored at one end. Work began an implementation not only of this algorithm, but of an experimental system incorporating an Adept robot, an AdeptVision system, and the planner. A preliminary three-level framework of *planning*, *qualitative control strategies*, and *traditional control* also emerged from this work.

A cut in funding caused us to combine the last year of our project with other research efforts in order to maximize the results usable by the Intelligent Systems and Robotics Center (ISRC). The final focus of the project was a push towards practical results in collision detection and motion plan-

¹When I grasp a book and slide it out from its space on my bookshelf, I am performing fine motions, because their planning and execution must exploit compliance and sensing. Moving the book to a spot in front of an empty space is a gross motion, it is planned and executed without including sensing or compliance. Modifying this motion in the middle to avoid hitting a lamp shade whose position was forgotten sensor-augmented control. Inserting the book is again fine-motion.

ning. The basic idea was to integrate the SANDROS motion planning algorithm with the C-Space Toolkit (CSTk) and a graphical interface. This was done, and improvements were made to both the CSTk and the SANDROS parts of the implementation to increase performance. The resulting system was three orders of magnitude faster than the previous version, which had used commercial software instead of the CSTk for distance computations. The current system is fast enough for the everyday motion planning of robotic manipulators and was reported in [23]. Furthermore, collision-avoiding motion segments are planned at interactive speeds, thus fulfilling much of the need for on-line plan repair. Finally, a fast swept-body distance algorithm was also developed and implemented. It was reported in [25] and can be used to enhance the ability of a mobile robot to look ahead of its motion and replan while moving.

2 Expanding Frameworks for Planning and Plan-repair

We began the project by investigating ways to expand frameworks for planning and plan-repair. We obtained the following preliminary and unimplemented results: (a) a theoretical method for extending fine-motion plans with reactive plan repair; (b) an analogous approach for gross-motion plans; and (c) a method that combines fine- and gross-motion planning.

To link theory with the practical, we supported related ongoing research in the mobile robot domain at Cornell University. The general topic of this work was building, using, and repairing models of the world for robust path-planning and execution. The short-term goal was to ensure the existence of an experimental system on which we could collaboratively check the feasibility of our theoretical achievements. Towards the goal of implementing our planning methods, this project also contributed funding support to the development of the C-Space Toolkit [26].

In this section, we first provide some background on the problems we considered. We then briefly present the preliminary theoretical results mentioned above and provide an overview of the progress made at Cornell for this project.

2.1 Preliminaries: Backprojections and Pre-images

We now describe a couple of technical terms from fine-motion planning. First, relative to a commanded compliant motion, a motion error cone, and obstacles, the *strong backprojection* of a set of states Y is the set of states X such that a motion beginning (at a state) in X is guaranteed to reach (a state in) Y under the commanded motion despite the possible error.² In Figure 1(a), $W \cup Y$ is the strong backprojection of Y under the commanded motion and the control uncertainty shown. The *weak backprojection* of a set of states Y is the set of states X such that a motion beginning in X is might possibly reach Y under the commanded motion, taking into account the possible errors. Second, relative to a commanded compliant motion, a motion error cone, obstacles, a mo-

²Basically, in compliant motion, if the commanded motion encounters an obstacle surface, it is projected onto that surface. Friction or friction-like effects can cause sticking when the projected vector is non-zero. An error cone is a solid angle about the commanded motion direction that encompasses possible directional error. See Figures 1(a) and 1(b).

tion termination predicate,³ and friction, a *pre-image* of a goal G is a set of configurations R such that a motion beginning in R is guaranteed to terminate in G and only in G . Figure 1(b) shows an example using blocking termination.⁴ The usual approach to fine-motion planning is to backchain pre-images, generating subgoals, until the set of possible start states is contained in a pre-image [18].

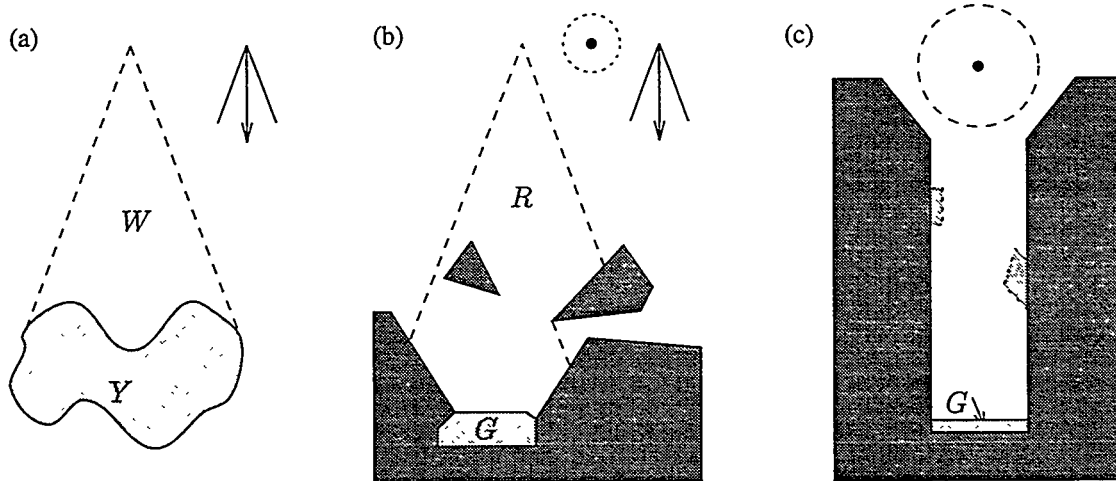


Figure 1: Fine motion planning (a-b), and a case requiring extension (c). In (b) and (c) the dotted circles represent position sensing/control error.

2.2 Tolerating Model Uncertainty and Errors with Reactive Strategies

We extended the fine-motion planning framework with limited reactive plan repair that enables plans to withstand qualitative model uncertainties and errors that could previously not be handled.

The construction of pre-images requires exact knowledge of the world and robot geometries. The fine-motion plans synthesized only tolerate uncertainty in position-sensing and control. Tolerancing can extend these techniques to cover *small* variations in surface normals and feature location, but this approach breaks down when the normal-direction variations are larger, even when the deviating features themselves are very small. The extended methods can fail even in simple cases — for example, that shown in Figure 1(c), in which the features shown with dotted-line boundaries can appear at unknown locations along the vertical shaft faces. These methods are inadequate regardless of the size of the protruding features in the example.

The basic idea of our approach is to use local, execution-time strategies to augment fine-motion plans. A nominal model of the environment and a model of possible deviations from this model

³A motion termination predicate is a function that monitors sensor values, possibly including time and position, and decides whether to terminate execution.

⁴Under blocking termination, plan execution terminates when forward progress is prevented.

are given, and a fine-motion plan is constructed for the nominal environment. Strategies are constructed to escape the class of possible deviations. We refer to the pre-image associated with an FMP-step, the corresponding (sub-)goal, and the nominal C-space obstacle as the *nominal pre-image*. At execution time, the nominal fine-motion plan and the local strategies alternate, with the former proceeding until a state unexpected under the nominal model is encountered, and the latter proceeding until it is determined either that the former can resume or that the current configuration is outside the geometric projection of the nominal pre-image. If the nominal plan is resumed, then execution terminates when either the goal is reached and recognized or failure is correctly recognized. Thus, this intuitive framework extends the error-detection and recovery (EDR) approach of [9]. However, it is important to note that if execution-time plan recovery is attempted, the guarantee that both success and failure can be recognized is only preserved when the plan recovery terminates successfully.

We also attempted to develop methods of endowing our extension with EDR properties. We considered a subroutine model of execution in which a local strategy always returns to the FMP that “called” it. Our analysis covered our extensions in the context of a single FMP-step and the associated (sub)goal.

We derived several necessary conditions for EDR correctness of the composite plan. First, the FMP step and possible model deviations cannot result in reaching a state that the FMP executor cannot distinguish from the goal. Second, if the FMP step and possible model deviations can result in a motion that leaves the nominal pre-image without returning to it, then a state must be reached that is recognizably outside the nominal pre-image. Third, if a state outside the nominal pre-image is recognizably reached, then the reactive strategy that would execute must result in a state that is outside of the strong backprojection of the “bad” state that is either recognizably in the nominal pre-image of the goal or recognizably outside of this pre-image.

Attempting to derive a sufficient set of conditions was more difficult. While the first two necessary conditions seem to translate directly, the third one does not. Escaping the strong backprojection but not the weak backprojection of the states associated with the deviation obviously leaves open the possibility of an infinite loop. Even worse, escaping the weak backprojection leaves open the possibility of bouncing back and forth among two or more anomalies. Putting aside hope for a minimal set of sufficient conditions, we proposed that for a plan to be continuable, the escape motion must achieve a state that is within the pre-image of the goal and that is closer, under some progress measure, to achieving the goal than the furthest previous state before the state that triggered the “escape” motion. An obvious choice of progress measure is distance in the original commanded direction.

Making this framework constructive (beyond the examples we have worked out) posed several problems. A question arises as to how reactive strategies themselves would be automatically synthesized. For this, we could bootstrap using fine-motion planning; given a parameterized deviation, we construct the problem of escaping it while remaining in the pre-image of the nominal FMP. It appears that the compositional scheme could be used recursively to tolerate qualitative uncertainties in the deviations themselves. One complication is that our sufficiency conditions imply that in order for pairs of deviations and reactive strategies to be treated individually, no two (C-space) deviations

can be located so that the reactive strategy for one can result in entering the other. Other questions remain, such as how an executor should distinguish between deviations that require different reactive strategies, and how to cope with changes in the (sub)goals due to model deviations. Finally, these methods face a familiar problem in fine-motion planning — how to represent geometric sets when the C-space is not low-dimensional (up to three or four degrees of freedom).

2.3 Combining Gross-motion Planning with Reactive Repair and Fine-Motion Planning

A framework for reactive plan repair to gross-motion plans faces the difficulty that there are no analogues of pre-images and subgoals inherent in most gross-motion methods. We have developed two preliminary approaches. (See Figure 2.) In the first, the path of a gross-motion plan is augmented by a “safety-tube” that surrounds it in the nominal environment mapped to configuration space (C-space), and reactive strategies attempt to avoid obstacles while staying within the tube. The safety-tube is analogous to the pre-image, and progress “along” the path is analogous to progress in the FMP-step direction. However, the problem arises that a configuration inside the tube can correspond to many points along the path, and for any given point on the path it is difficult to compute the cross-section of the tube at that point. A second approach is to introduce subgoal regions or point that the GMP path passes through. This can be done by extending a two-level planner (e.g., [8]) whose local planning element models the execution-time system that governs motion between witness points in subgoal regions. Such a plan becomes resumable (during execution) when the local planning element can find a path to the next subgoal, taking into consideration current (C-space) obstacle information obtained by the reactive element. As in the FMP case, a deviation must not occur where it can interfere with a reactive strategy coping with a different deviation. Unlike the FMP case, GMP subgoals are usually defined strictly by position, leaving the problem of how a robot would recognize a subgoal. However, work in map-making, localization, and robot navigation, such as [10] and [1] offers promise. Specifically, we would combine “classical” GMP subgoals with a minimal version of the reachability-recognizability graph (which includes sensing) [10], augmented with *a priori* world knowledge. We note that the adaptive path planning work of [7] attaches subgoals to obstacles rather than fixed coordinates.

The investigation into the repairability of GMPs is closely related to a method we have proposed for integrating fine-motion and gross-motion techniques into one planner. From an abstract viewpoint, we generate and search a graph containing: f-nodes, which are FMP pre-images; g-nodes, which are GMP points or subgoals; f-edges, which begin at f-nodes; and g-edges, which begin at g-nodes. (Search direction tends to be opposite from edge direction.) Two main problems arise: the computational cost of pre-images can be high and varies with complexity of subgoal kernels [18] used, and the “natural” branching factor (in and out) at f-nodes is large. We see two techniques, which can be combined, to attack these problems. First, by requiring each (sub)goal kernel to contain one or more cells not contained by another kernel, we can bound the overall number of nodes according to a discretization. Second, we consider the related pure GMP problem in which an edge is only considered “dirty” if it might be invalidated by uncertainty, and use minimum-dirty-edge

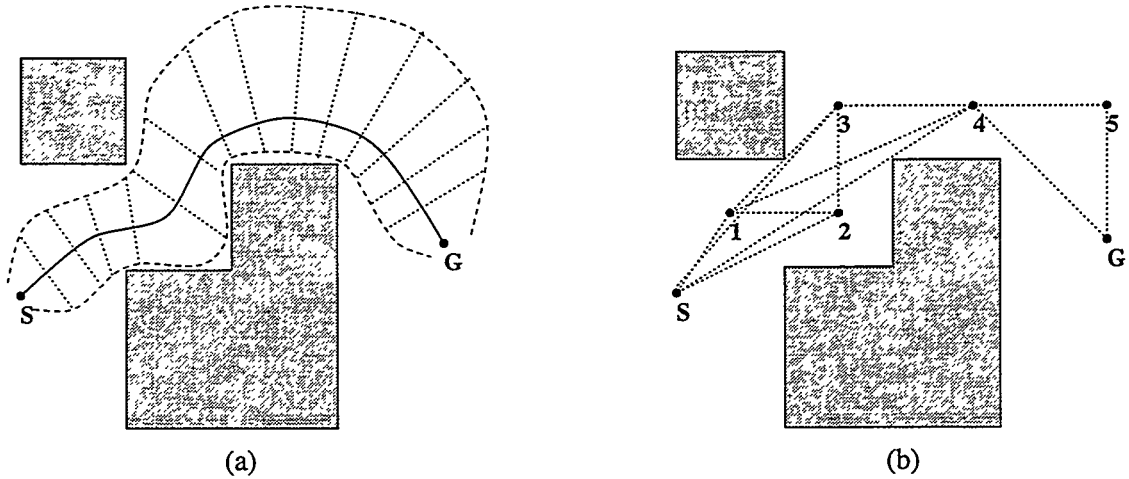


Figure 2: (a) Repairable gross-motion plan using the safety-tube method. (b) Gross-motion plan using point subgoals.

paths to heuristically guide the kernel generation and pre-image generation. We note that although the former could damage the completeness of the algorithm, this is acceptable because complete fine-motion planning is intractable (NEXPTIME-hard) anyway.

Although we believe that our approaches for plan gross-motion plan repair and for combining gross- and fine-motion planning could be implemented for low degrees of freedom (three or less), the need for explicit construction of C-Space sets made practical implementations impossible for higher-DOF systems. This situation holds to this day.

2.4 Work Towards building, using, and repairing models of the world for robust path-planning and execution on a Mobile Robot

A mobile robot is an ideal platform on which to test methods of building, using, and repairing models of the world for robust path-planning and execution. By FY1994, exploration of mobile robotic navigation and localization was already in progress at Cornell University, using two mobile robots (TOMMY and LILY) that had been developed in the four preceding years in the laboratory of Prof. Bruce Donald. As study of coordination of robotic motion, sensing, and control in plans and execution meshed well with Dr. Donald's research program, we reached a contract for a semester of research by (then) graduate student Russell G. Brown towards this end. What follows in this section summarizes the final report [3] for this work, and additional details can be found in [2].

LILY itself was an omnidirectional indoor mobile robot built on an RWI base and equipped with a ring of contact sensors, a ring of sonar sensors, and a pan/tilt three-beam laser rangefinder that was developed at Cornell. Onboard computation was provided by a 12mHz MC68HC100 microcomputer with 2.5MB of RAM.

Three main technical achievements occurred during the contracted research period.

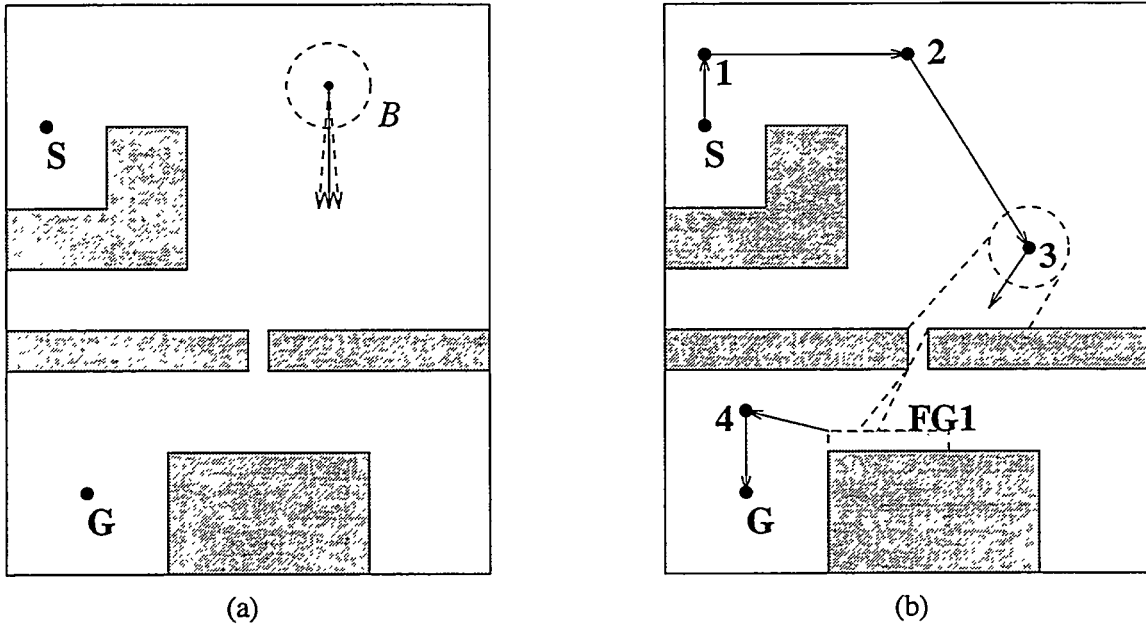


Figure 3: (a) Problem, showing start and goal, positional and directional control uncertainty. Contact detection and sliding are presumed. The goal is a GMP goal, so achievement to within positional uncertainty is acceptable. (b) Combined GMP and FMP plan; FMP subgoal is FG1. The GMP part of plan is needed to get into and through the narrow passage.

First, the Cornell researchers developed, implemented, and tested a mobile robot localization algorithm designed especially for their laser-rangefinder sensor. This algorithm uses a rasterized, directional flood-fill technique to compute the discrete convolutions of the range error and the inverted distance vector with a discretized map. Basically, the difference between these two convolutions yields the set of feasible poses for the mobile robot.

Second, LILY's map-making software, which is a rasterized, discretized implementation of the *Statistical Occupancy Grid* algorithms of [20] was integrated with the localization software. This achieved the second goal of the contracted research — to have implemented techniques with which a mobile robot could explore an indoor test area and construct annotated maps matched to its sensing, its control, and its localization algorithm.

Finally, the Cornell researchers made progress toward path-planning and execution techniques enabling a mobile robot to tolerate errors in its maps and to recover from errors in execution of its paths. A flood-fill potential-field motion planner was implemented; a plan thus provides the robot with incremental motions that lead to the goal from any unoccupied point in the mapped region. At execution-time, the localization algorithm is used intermittently to detect and compensate for navigation errors due to dead-reckoning (and compass inaccuracy). A multi-versioning technique was proposed to enable sensor-based map updates while enabling recovery from erroneous updates due to navigational error. Use of the localization algorithm, time-varying map information, and

changes in measurement stability were proposed for distinguishing navigational errors from map errors. Unfortunately, memory limitations prevented implementation of the multi-versioning map maintenance scheme.

Our research using mobile robots were severely hindered when Dr. Brown was hired by Sandia but placed on another project and directed away from mobile robotics.

3 On sensing, planning, and execution for flexible objects

Extending familiar configuration-space techniques led us to approaches that met our theoretical goals for FY1994 but appeared impractical for systems with more degrees of freedom. When staffing and resource problems made it difficult to pursue our investigation of these problems on mobile robots, we considered other problem domains in which to continue our work.

We concluded that the deep research issues would be better and more generally addressed by considering flexible objects in the plane as the domain. Flexible objects naturally generalize high-degree of freedom kinematic chains. We expected that the restriction to the plane would reduce the implementation burden but still would allow results of practical interest. Specific expected areas of impact included (a) the automatically planned and executed robotic manipulation of flexible cables, cable harnesses, and several common varieties of springs in manufacturing, and (b) autonomous robotic management of tethers and hoses during the inspection or painting of ships and aircraft and in environmental cleanup, plant decommissioning and disassembly.

Changes to our milestones and work plan were detailed in a January 17, 1995, memo to the LDRD Office.

3.1 Three Planar Flexible Object Problems

We carefully formulated a progression of planar flexible-object manipulation problems for a robot with a simple vision system and (if necessary) force-sensing wrist. The progression of problems parallels that from gross-motion to fine-motion planning and execution. In addition, these problems were chosen because they believed to be intractable using C-space methods.

The first problem is a gross-motion problem that cannot be reduced to a C-space search: A nearly ideal (infinitely flexible) cable lies among obstacles on a planar surface, with one end fixed. The task is to move the free end of the cable from its current position to a goal position along the shortest path possible. The cable never leaves the surface, except to cross itself (in one version of the problem). It is presumed that the obstacles can be found by thresholding, that the fixed end of the cable is identified, and that the goal position is identified on the camera output.

The second problem is a manipulation task with incomplete control and a quantitatively weak model: A cable lies among but not touching obstacles on a planar surface. The cable is very flexible but not necessarily nearly ideal, and its minimum radius of curvature and shape preference are unknowns that can vary along its body. A path from one end (free, if the other is fixed) of the cable to a goal position is given. The task is to move that end of the cable to the goal along some path

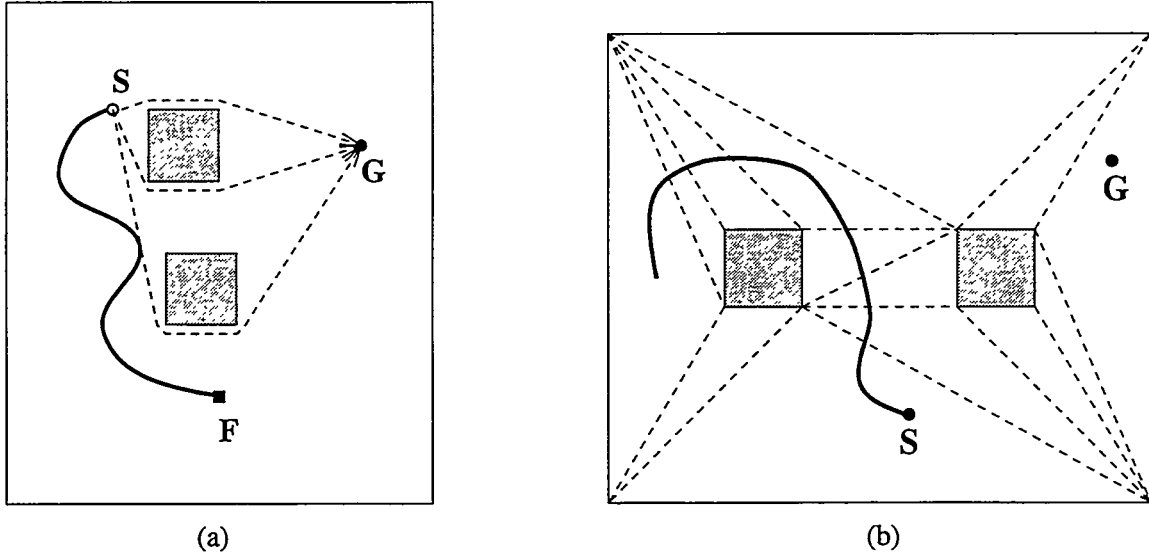


Figure 4: (a) The anchored-cable shortest path problem. The anchor point is the solid square at one end of the cable, and the open circle is the cable's free end. The shortest path for the free end depends on the length of the cable. (b) An unanchored cable manipulation problem: the cable can only be grasped at one point at a time and may not touch any of the obstacles. A Delaunay triangulation is also shown for example purposes.

in the same homotopy class as the given one; the cable may not touch any of the obstacles, and the robot can only grasp the cable at one point at any given time.

The third problem considers the manipulation of an arbitrary simple (no closed loop) flexible planar object. The object is skeletal; specifically, it is composed of rigidly attached cable segments. The goal is to manipulate the object so that specified contacts with fixed, rigid objects in the environment are realized. The practical motivation for this problem is the automated robotic grasping, fixturing, and assembly of flexible parts.

The remainder of this section describes work done in the flexible-object domain, mostly toward the first problem. Unfortunately, at the beginning of FY1995 Q4, the project's funding was cut in response to the change in milestones. In response to the cut in funding, the project changed direction yet again to enable the ISRC to maximize the usable results from the project. (See Section 4.)

3.2 Path Planning Algorithms

We developed algorithms for planning shortest paths for the free end of an anchored cable among obstacles in the plane, both for the case in which the cable is allowed to cross itself and for the case in which it is not. These algorithms have running time $O(N^4)$, where N is the number of obstacle vertices, but also have "anytime" versions that can produce valid but suboptimal answers (when they exist) in time $O(N \log N)$ and improve optimality thereafter.

Our path planning algorithms make use of known algorithms for three sub-problems: Delaunay triangulation (DT, done in $O(N \log N)$ time), planar visibility graph calculation ($O(N^2 \log N)$), and single-sink shortest paths ($O(N^2)$). We introduce a new (sub)-algorithm that exploits the DT to calculate the “pulled taut” configuration (PTC) of a path or a cable configuration in $O(N \log N)$ time; that is, for a given cable configuration, we can determine the shape that would result if it were pulled down through the plane at the free-end location until taut. A variation covers the computation of the PTC of the cable after a series of linear motions of the free end, each of which might pull on the cable. The correctness proof relies on homotopy and shape properties of the PTCs. The planner is guaranteed to succeed whenever there is a solution. The planner can also use the DT to assure it does not produce a path passing through gaps too tight for the gripper.

This algorithm is definitely practical to implement, and an implementation has been mostly completed. A paper describing this implementation, as well as providing the details of both the algorithm and the proof, is expected.

3.3 Plan Execution

In our model of planning and execution, the executor’s role is to make queries to the sensing module and the planner and, using this information, send commands to the robot controller; these commands might involve how the controller should use sensor information. In this discussion, the executor assumes the visual information has been significantly postprocessed so that the obstacles are represented by the union of convex polyhedra and the cable is represented by the list of points corresponding to image pixels on its midline.

For the planner described in the previous section, the executor has two tasks: (a) achieve an endpoint grasp of the cable; and (b) post-process the planner output to choose knotpoints that enhance path safety. We developed a simple algorithm (strategy) for (a): the robot finds the graspable point on the cable nearest the free end, loosely grasps it, and then slides the gripper up towards that end along the Voronoi diagram of the environment. If at some point the obstacle gap is too tight, the robot executes a series of “pull back” and “slide up” moves until it reaches the cable end (easy vision query). Note that the “sliding up” does not have to literally slide, but can be done as a regrasp. We also developed an algorithm for (b) that uses PTCs to conservatively estimate how much cable slack is available at each vertex in the planned path. This is then used to compute the maximum displacements beyond which the cable length constraint would be violated.

We began implementation of an experimental system based on an assembly workcell consisting of an Adept 2 Robot, an AdeptVision vision system, a force-sensing wrist, an Adept Controller, and a UNIX workstation. The physical set-up and communications software reached a near-complete state. The remaining algorithms, including those needed at execution time, were finished and ready for implementation.

Our experimental system design assumes a known set of obstacle shapes. We would use the AdeptVision system to identify and approximately locate the obstacles; we would simply train the system on the individual obstacles beforehand. The approximate locations would be used as input to a filtering algorithm that better locates object vertices on the image plane — that is, directly in

the sensor space calibrated with the robot controllers. The filtering algorithm is conservative in that the actual obstacle can be a subset of the filter output. This output would be used by the planner and executor. The gist of our analysis method is that by tying the planner and executor directly to the calibrated image plane, we assure that they are reliable, with respect to the information available from the sensor and model combination, to the robot's vision and control accuracy/calibration. Our filtering algorithm makes extensive use of software provided with the AdeptVision system and would be simple to implement.

3.4 Qualitative Control Strategies

We also made preliminary progress towards a solution strategy for the second cable problem. The basic idea of the strategy is to create and propagate forward slack relative to obstacle distance. The strategy would exploit concurrent translation and rotation of grasp points and the fact that the resulting motion normal to the cable decreases with distance from the manipulation point. A possible proof approach would use an adversary game: moves by the adversary would form a superset of the possible effects of each cable manipulation, thus accounting for the uncertainty or model incompleteness. Proving the strategy succeeds in the game assures the success of the corresponding sensing and manipulation strategy under the corresponding range of physical conditions. A key element is an algorithm for qualitatively predicting cable motion in repose to an action. An algorithm that qualitatively modeled the effect of pulling was developed and implemented, but we were unable to make much progress on the effect of pushing.

This strategy would be an example of a *qualitative control* algorithm, computations and actions that execute below the usual planning level but above the usual control level. In the framework that emerged in this project, the precise role of the qualitative control level is to guarantee a series of transitions between the states used at the plan level, terminating with the goal. In the first cable-motion problem, the plan consists of a series of qualitative states of the cable — the sequence of DT cells from its anchor point to its free-end in combination with the sequence of DT cells the free end must move through. The qualitative control level for the system is the sensing, end-effector path planning, grasping, and ungrasping strategy that moves the cable through this series of states. Note that this is distinct from the control system of the robot. In the second problem, the plan is again a series of qualitative states, each of which is a series of edge-adjacent DT cells combined with the constraint that the cable must not touch the obstacles. The qualitative control level, however, is much more complicated, consisting of a strategy for finding slack or generating it at the tail of the cable, followed by strategy for propagating this slack forward.

4 Collision Detection and Motion Planning

New research opportunities arose as another LDRD project [26] reached its conclusion, providing us with the C-Space Toolkit geometry library, which we could exploit and build on while merging efforts with other projects in the Intelligent Systems and Robotics Center. By doing this, we were able to obtain two important, fully implemented results in motion planning and collision detection.

First, we integrated the SANDROS motion planner with the C-Space Toolkit (CSTk) and a general robot simulation and control package (Telegrip by Deneb Robotics). The final system we obtained is not only fast enough to be used interactively on an everyday basis, but is also fast enough so that it is reasonable to re-plan suitably sized motion-segments that would cause a collision. A second result is an algorithm for efficiently computing the distance between the volumes swept by two moving objects. This algorithm can be used for robust look-ahead in collision avoidance — for example, to determine whether a detour motion is necessary — as well as in various types of simulation.

4.1 Path Planning for Everyday Robotics With SANDROS

Path planning has an extensive history [14, 17], and recent results such as [5, 8, 13, 15, 16] provide feasible offline solutions, if not arguably online solutions. The SANDROS (for *Selective and Non-uniformly Delayed Refinement Of Subgoals*) planner [8] is among these, but its practicality was limited by the lack of a software geometry engine capable of answering exact distance queries quickly for geometric models of realistic complexity. During continuing work on SANDROS, we also encountered problems in finding examples on which to experiment, in modifying the experiments quickly, in getting quick experiment turnaround time, and in making SANDROS useful to robotic applications in our organization. To improve its performance, we integrated SANDROS with the C-Space Toolkit and made some improvements to both parts of the implemented system.⁵ To improve usability, we integrated SANDROS/CSTk with the Telegrip simulation and control front-end widely used in here in the Intelligent Systems and Robotics Center; however, this front end could easily be replaced with any graphical robot-programming interface.

The basic architecture of the combined SANDROS/CSTk/Telegrip planning system is shown in Figure 5. The simulation environment initiates the planning by invoking the control module with a description of C-space and the start and goal in C-Space. The control module extracts the geometry information from Telegrip, passes it to the C-Space Toolkit, and then initiates SANDROS. As SANDROS executes, it poses queries about the minimum distance between the robot and the obstacles at various points in C-Space. The control module takes these queries, obtains the necessary world transformations for each robot link from Telegrip, and then calls the C-Space Toolkit to compute the distances.

While most of this section summarizes [23], we now describe several optimizations not mentioned in that paper. Most of our optimizations are within the control module. First, the control module keeps track of which robot link yields the minimum distance, and asks the CSTk to compute the distance for this link first in the next query. Second, the control module keeps track of the minimum current distance during each query, and passes this as an upper bound to the CSTk, enabling it to prune its search. Third, the control module caches the results of each whole-arm distance query at different configurations. Fourth, the control module caches minimum-distance information for each link at each link configuration (6DOF) for which it calls the CSTk. This reduces the number of link-world queries made to the C-Space Toolkit. Finally, when it is necessary (as described in [8]) to re-check that the final path is safe, the control-module makes distance queries with upper

⁵This work was done in collaboration with other projects in the Intelligent Systems and Robotics Center.

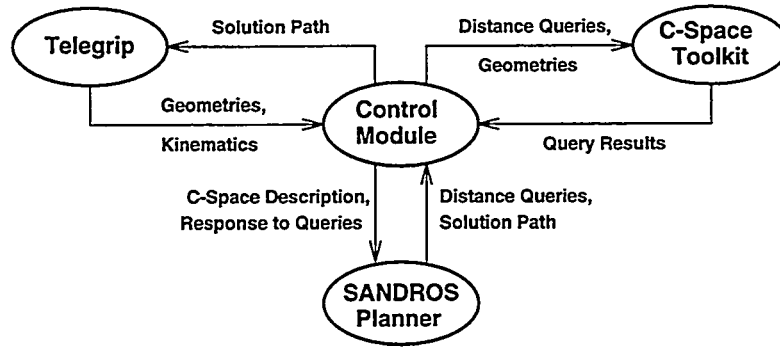


Figure 5: SANDROS/CSTk integrated with Telegrip.

bounds just large enough to verify safety.

An additional modification was tried deep inside the CSTk. The CSTk models objects as bounding volume (convex polyhedra) trees with convex polygons/polyhedra at their leaves and that it employs a recursive hierarchical distance algorithm[25, 26], instead of simply using a branch-and-bound search. The modified version of this algorithm maintains a *cut-table* of pairs of interior nodes for which it believes a comparison against the current best distance might cause a cut in the recursion. The pre-recursion check is only done on node-pairs in this table. The cut-table is incrementally maintained so that in equilibrium, the node-comparisons done are exactly those that yield cuts in using the branch-and-bound method. The point is to only use the pre-recursion check when there is a reasonable chance it might do some good. An alternative approach to achieving this goal is to cache node pairs that are *not* expected to be useful in bounding the search if the query were repeated (recall that minimum-distance witnesses are cached); if one of these cached pairs is encountered, we assume that computing the distance between them would not allow us to cut off the branch of the search, so we skip the distance check and instead descend further down the hierarchy. We implemented the first method and found it useful when the maximum number of vertices allowed on a convex wrapper was high. However, lowering this number and not using the cache was simpler and produced similar, sometimes better performance.

Several motion-planning experiments were done in “everyday” example scenarios — medium-sized problems free from pathological and semi-pathological cases, with geometries of up to 10K polygons. Planning times ranged from a few seconds to a couple of minutes on a Silicon Graphics (SGI) Indigo2TMR4400/250 and are two to three times faster on an R10000. An additional delay occurs the first time SANDROS is called for a given robot/environment pair, as the CSTk must load the geometry and initialize data structures. This takes about 30 seconds for a 10K-polygon example, and it has not been optimized.

Results using a spot-welding example shows that the power of SANDROS/CSTk at least partially renders moot some of our original questions about gross-motion-plan repair. In the example, an operator uses a mouse to select a series pre-determined weld points on a fender held by a fixture, successively invokes the planner to plan motion between points. We found that the planner running

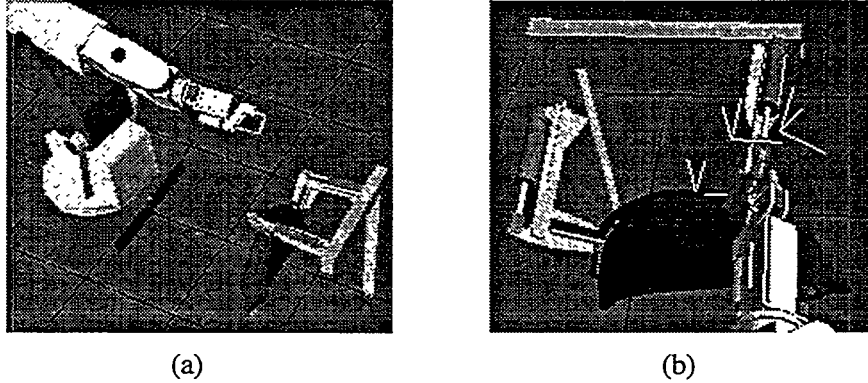


Figure 6: A spot-welding example. The close-up view in (b) shows the clamps the robot must avoid and some welding frames it must visit.

on an SGI Indigo2TMR10000/195 could plan the necessary motions, including detours around the fixture, just about as fast as an experienced Telegrip operator could select the points and invoke the planner from a pull-down menu. The significant implication is that even for full 6DOF robots, local replanning is, or will soon be (given expected increases in computer performance), fast enough so that gross-motion plan repair can be done simply by planning a new path segment to the next valid knotpoint/tagpoint. The bottleneck has now shifted away from planning algorithms to updating geometric models. (Results in this paragraph were not reported in [23].)

4.2 Fast Swept-Distance Computation for Robust Collision Detection

This section is mostly a summary of [25], which presents new, fast, implemented techniques for exact distance computation and interference detection between translationally-swept bodies and for improved approximate distance computation and interference detection when the sweep motion has a rotational component. Our techniques thus advance the capability to perform fast, accurate collision detection and contact determination. They thus have application in motion planning and on-line collision avoidance, as well as dynamical simulation.

At the heart of most current methods for *collision detection* are algorithms for *interference detection* and/or *distance computation*. A few recent algorithms and implementations are very fast (e.g., [12, 21, 22]), but to use them for accurate collision detection, very small step sizes may be necessary, reducing their effective efficiency. We have developed a fast, implemented technique for doing exact distance computation and interference detection for translationally-swept bodies. For rotationally swept bodies, we have adapted this technique to improve accuracy, for any given step size, in distance computation and interference detection. Preliminary experiments show that the combination of basic and swept-body calculations holds much promise for faster accurate collision detection.

Our algorithms are based on three simple observations. First, although Gilbert's Algorithm [11]

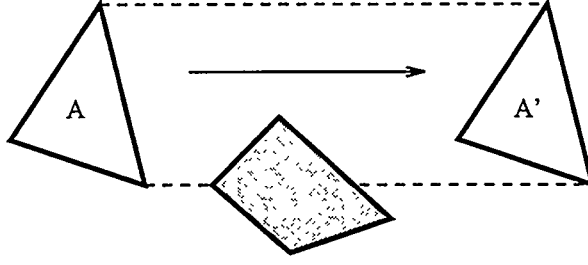


Figure 7: Between queries, the triangle moves linearly from A to A' . Because there is no interference with the obstacle at the query times, simple interference checking fails to detect the collision with the obstacle. Basic distance queries at the query points would indicate that it might be possible that there is a collision, but further computations would be needed to decide. The swept hull of the moving triangle intersects the obstacle, so a swept-body interference check would detect the collision.

is usually applied to convex polyhedra and convex polygons, it can do more: given two finite sets of points, it computes a minimum distance vector between their convex hulls. Second, the convex hull of the vertices of a polyhedron (polygon) and their images under a translation \mathbf{x} is equal to the swept hull of that polyhedron (polygon) under translation \mathbf{x} . Thus, we can use Gilbert's Algorithm to compute the distance between the volumes swept by two polygons or polyhedra under linear translations. We do this by adding the new positions of the vertices to the lists of input vertices. Third, if A , B , and C are convex and $A \cup B \subset C$, then

$$\text{sweep}(A, \mathbf{x}) \cup \text{sweep}(B, \mathbf{x}) \subset \text{sweep}(C, \mathbf{x}).$$

This means that the *conservative approximation* nature of our hierarchies is preserved under translation.

To apply these observations, we assume that objects are represented by convex-polyhedral bounding volume hierarchies, such as those constructed by the algorithm presented in [24], possibly with the augmentations given in [26]. We then consider a basic hierarchical distance algorithm (as in Figure 1 from [25]), and modify it: for each distance computation between two convex polyhedra (or polygons), we augment the vertex lists to include the vertices in their new positions. The resulting distance computation is the exact distance for linear translational sweeps. With the help of some simple trigonometry, we can also derive the approximation achieved when each linear motion is combined with a simultaneous rotation. This approximation can be made conservative by extending a technique from [19]. In both cases, the approximation is $O(r\theta^2 + l\theta)$, where θ is the angle of rotation, r is the radius of rotation, and l is the diameter of the longest polygon (or polyhedral leaf) in the geometry.

We implemented these algorithms as an extension to the existing C-Space Toolkit, and carried out a set of simple experiments for linear translational sweeps. These experiments [25] compared query bandwidth for distance computation, swept-body distance computation, interference detection, and swept-body interference detection, both with and without closest/contact witness collection. The two test scenarios had 10K and 52K polygons, and speed on an SGI Indigo2 R4400/250

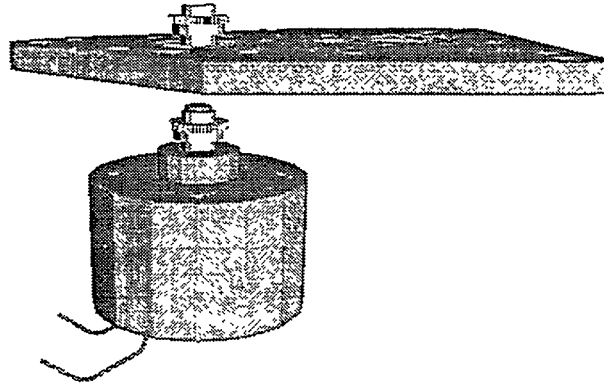


Figure 8: A swept-volume distance computation or interference detection example with tight tolerances and semi-pathological difficulty due to concavities and symmetries. The moving gear is shown at the middle and the end of its path downwards.

ranged from 8Hz on a semi-pathological case to 140Hz for the best case, with 40Hz being most typical for swept-body distance and 100Hz being typical for swept-body interference. We found that computing linear-translational swept-body distance was no more than 50 percent more expensive than ordinary distance computation. Analysis of the rest of this preliminary data indicates that using the swept-body distance method will be more efficient than using ordinary distance computation to determine: (i) whether a linear translation causes interference, (ii) which pairs of polygons interfere during the motion, and (iii) what are the contact initiation and termination points during a timestep. Full computation of (iii) requires a space-time method [4, 6] to be applied to the candidate pairs of polygons and polyhedra returned by the swept-body analysis. Finally, we note that there is no known way for extending the OBB technique used by [12] for fast interference detection (probably the fastest currently) to handle the swept-body case.

5 Conclusion

Our project began with the goal of developing a framework for robotic planning and execution that provides a continuum of adaptability with respect to model incompleteness, model error, and sensing error. In the first year we developed theoretical methods that combined and extended gross-motion and fine-motion planning; additional (contracted) work produced preliminary results for a mobile robot platform. Staffing problems and a realization that our theoretical results would not extend to high degrees of freedom led us to choose a new domain — flexible objects in the plane. This domain generalizes high-degree of freedom kinematic chains, and the planar restriction promised to simplify implementation. Our results included a planning algorithm for a planar cable anchored at one end, a proposed planner-executor framework, and experiment design and partial implementation.

Project funding was scaled back in response to our changed project plan. This led us to combine the last year of our project with other research efforts in order to leverage. We obtained two significant results. First, we developed and implemented a fast swept-body distance algorithm applicable to collision-avoidance, motion-planning, and simulation. Second, we integrated Sandia's C-Space Toolkit geometry engine and SANDROS motion planner and tuned the combination. The resulting system is not only practical for everyday motion planning but plans motion segments at interactive speeds without having the limitations of potential-field methods. It is thus suitable for making revisions to motion plans on-line and can serve as a key element in a coordinated sensing-planning-and-control system.

These latter developments continue to be used and are being built upon in continuing work in the Intelligent Systems and Robotics Center. Implementation of our cable-planning algorithm progresses when resources are available, and we believe that this algorithm will eventually be used in a robotics projects involving an anchored tether or cable.

A Project-Related Information

Awards: None.

Publications and presentations:

- P. Watterberg and P. Xavier. "Path Planning for Everyday Robotics With SANDROS", *Proc. 1997 IEEE Int'l Conf. on Robotics and Automation*, Albuquerque, NM, April 1997, pp. 1170–1175. Presented, April 1997. (Work collaboratively funded with other projects.)
- P. Xavier. "Fast Swept-Volume Distance for Robust Collision Detection", *Proc. 1997 IEEE Int'l Conf. on Robotics and Automation*, Albuquerque, NM, April 1997, pp. 1162–1168. Presented, April 1997.
- Y. K. Hwang, P. G. Xavier, P. C. Chen, and P. A. Watterberg. "Motion Planning with SANDROS and the Configuration Space Toolkit, in *Practical Motion Planning in Robotics: Current Approaches and Future Directions*, edited by K. Gupta and A. P. del Pobil, John Wiley & Sons, Ltd., New York, *prospective book title, to appear*. (Work collaboratively funded with other projects.)

Patents: A Disclosure of Technical Advance (S-88,419 / SD5999) was filed for our fast swept-volume distance algorithm.

Copyrights: C-Space Toolkit, Version 1.0. This project's main contribution was the swept-volume distance algorithm. (See Section 4.2.) Most of the rest of the CSTk was previously completed under a previous LDRD.

Follow-on Work: The fast swept-volume code is being used in two current LDRD Projects: "Content-Based Search of Geometric Databases" and "Dynamic Simulation of Mechanical Systems with Intermittent Contacts". It is also expected to be used in the "Immersive CAD" LDRD project, our Small, Smart, Machine simulator, and an upcoming LDRD on 3D model acquisition entitled "Cloud to CAD". Additional follow-on work includes a 3D mobile-robot map-model-explore-plan prototype system.

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