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Tactile Robotic Mapping of Unknown Surfaces: an Application to Oil Well Exploration

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Abstract— World oil demand and advanced oil recovery techniques have made it economically attractive to rehabilitate previously abandoned oil wells. This requires relatively fast mapping of the shape and location of the down-hole well structures. Practical factors prohibit the use of visual and other range sensors in this situation. Here, the feasibility of robotic tactile mapping is studied. A method is developed that only uses the robot joint encoders and avoids any force or tactile sensor, which are complex and unreliable in such a hostile environment. This paper addresses the general problem of intelligent tactile exploration of constrained internal geometries where time is critical. It is assumed that the time required to move a manipulator to acquire a new touch point outweighs computational time. This approach models the down-hole structures with geometric primitives and focuses on exploration efficiency by intelligently searching for new touch points to build the geometric models. The algorithms developed here are shown in simulations and hardware experiments to substantially reduce the data acquisition effort for exploration with a tactile manipulator.

Keywords- autonomous exploration, robotic mapping, tactile sensing, surface reconstruction, oil-well exploration

I. INTRODUCTION

Rising world oil demand and advanced oil recovery techniques have made it economically attractive to rehabilitate previously abandoned oil wells. This requires lowering instruments and tools into the wells. These wells often have a number of junctions where divergent branches leave the main well at unrecorded depths (Figure 1). To rehabilitate an abandoned branch, the location and shape of its junction needs to be determined. The data acquisition to map a junction must be done quickly given the very high cost of keeping a well out of service (tens of thousands of dollars per hour).

Well mapping is challenging because the opaque fluids that fill the well to avoid its collapse prevent the use of visual or laser sensors to measure the junction. Ultrasonic sensors have been suggested for this application, but studies have yet to show that they posses the desired performance in down-hole conditions. Also a layer of “mud cake” often obscures the well bore surface. Consequently, robotic tactile exploration is appealing. Here the feasibility of using a manipulator lowered into the well to measure the junction location and geometry by probing is studied in simulation and hardware experiments. The mechanical design of a manipulator to function in the down-hole environment of an oil well with its extreme temperatures is difficult and beyond the scope of this paper. Here the focus is on the general problem of intelligent tactile exploration of constrained internal geometries where time is a key factor.

Exploration and measurement using tactile data presents unique challenges compared to using visual or other range sensors. Obtaining tactile data is expensive in terms of time. One visual image can very quickly provide thousands of data points for an object surface. In comparison, the time for moving a manipulator to acquire tactile data outweighs its associated computation and processing costs. Hence, the key to efficient tactile characterization is the intelligent selection of where to search for new touch points.

In this work, a new strategy is proposed that is well suited for the exploration of general unknown shapes in hostile environments when time is a key issue. This work chooses the oil well mapping as a representative case, but it uses a general approach that can be applied also to similar situations such as pipes, mines or nuclear facilities. This approach is based on the use of surface fitting to characterize geometries, subject to the assumption of sparse data collection. The environment to be mapped is represented as the composition of a set of geometric primitives. The approach continuously rebuilds the map as data are acquired. The search for additional data points is directed based on the information obtained at the current point in the process. The objective is to minimize the time of the search, and similarly the distance traveled by the manipulator end-

![Figure 1. Typical oil well branching structure with cutaway detail of a junction showing deployed tactile inspection manipulator](image-url)
point, to reconstruct the unknown surface to a given accuracy. This search should maximize the amount of new information provided by each data point and thereby minimize the number of data points needed to generate the map.

The proposed architecture is tested and compared in simulations and hardware experiments. The results show the effectiveness of the proposed search method in terms of time, traveled distance and data points needed to map the unknown surface.

A. Previous works

Studies on robotic tactile exploration have been driven by research in different fields: robotic grasping and manipulation [1], reverse engineering [2] and computational geometry [3].

Early studies developed techniques for locating and identifying polygonal objects among a library of known models [4]. In these works, the search for new data is selected to reduce the possible object interpretations according to the known library. More recent works in haptic exploration identify local features on the object by analyzing the surface curvature [1].

Approaches for general, unknown objects have also been formulated. Interesting exploration strategies have been developed describing the object surface with a mesh, and guiding the robot motion to make this mesh arbitrarily dense [3] [5] [6]. While a mesh is an effective representation of a general surface, it requires dense data to completely represent a generic object, and it is not efficient when the exploration time is an essential factor. The same requirement occurs when a spline is used to represent the object [7]. An alternative approach represents surface geometry as a composition of primitives, such as planes, cylinders and spheres. These primitives are often determined with curve and surface fitting methods [8]. Alternatively, they can be determined using differential invariants [9]. All these methods use either a dense, evenly spaced grid to collect data points, or assume that the data have been previously collected. The importance of intelligently selecting where to collect data for effective exploration has been recognized in [2], but the method in this work is still tied to a grid sampling concept and therefore inherently uses dense data.

With regard to the hardware needed for exploration, all the studies mentioned use either a force-torque sensor, or an active tactile probe. The method presented in this work only requires information from joint encoders. Contact detection using only data from joint encoders has been studied in the context of multifinger grasping [10] [11]. Yet, these works study only local contact detection, and not the issues of surface reconstruction and exploration.

In conclusion, while different works studied intelligent exploration, characterization of general unknown geometries, and sensorless exploration, the integration of these concepts in a unified method that allows the efficient exploration of hostile environments remains yet totally unsolved.

II. SENSORLESS ROBOTIC TACTILE MAPPING OF AN UNKNOWN ENVIRONMENT

Consider a manipulator inside an arbitrarily shaped environment, with its base fixed to this shape, see Figure 2. The objective is to tactily create a map of this environment with the minimum travel by the robot. By touching the surface with its tip, the robot autonomously collects data points and reconstructs the shape within a given accuracy. The oil-well junction mapping is a particular instance of this general problem.

The manipulator is controlled with an impedance control scheme [12]. This permits the robot to press against the surfaces without any force or tactile sensors. Impedance control is used to hold the manipulator probe against the environment. The position of the probe tip and therefore the contact point on the surface can then be determined just by sensing joint angles. The absence of force sensors makes this approach inexpensive, robust, and suitable for harsh environments.

In this work, the environment surface is assumed to be rigid and composed of any combination, as in constructive solid geometry, of the following primitives: planes, spheres, cylinders, cones and tori. This choice is general enough to represent a high number of surfaces (a survey by [13] indicates that 95% of conventional objects can be represented by these primitives), and it is easy to generalize to further shapes in case these primitives prove to be insufficient. In fact, blends between primitives can be implemented, and splines can be locally used in situations where no primitive represents the real shape.

This exploration and characterization architecture allows for fast determination of large-scale elements of a general geometry. This characterization can be used later to guide intensive small-scale tactile exploration of designated areas of interest, such as the lip of a junction in an oil well.

The overall goal of tactily mapping the shape of the environment with a robot can be divided into two problems that are solved simultaneously: surface reconstruction, dealing with the representation of the shape, and exploration strategy, dealing with the best exploring path for the robot.

Figure 2. Robot for tactile mapping in a generic environment
A. Surface reconstruction

The objective of surface reconstruction is to best represent the surface given the points touched on it. This process is iterated every time a new point is measured and the surface model is re-evaluated. Surface reconstruction has been well studied in reverse engineering for large, dense datasets from range sensors. This work adapts these techniques to small, sparse datasets from tactile data.

As mentioned before, the surface is represented as a combination of primitives. The parameters of these primitives are determined with a least squares approach, minimizing the sum of the squared distances between primitive and data points. Different solutions for this problem, called surface fitting, have been proposed [14] [15] [16]. Among these algorithms, tests showed that the method in [16] worked the best for small and sparse datasets characteristic of tactile exploration.

In order to correctly fit the data to different primitives, these primitives need to be detected, and the points classified so that each point belongs to only one primitive. This problem is called range data segmentation. Among the several methods proposed in literature, an approach called fit and grow has been chosen and implemented [17]. It is based on the selection of small initial regions to which all the possible primitives are evaluated. Regions that give a good fit are then gradually expanded. This approach is chosen because it best fits our particular application where sparse points are added to the dataset gradually, and outliers can be present when a primitive has been just partially discovered.

After the primitives are identified, their intersections are computed to produce the complete representations [18]. Care must be taken, and some primitive parameters need to be modified, in order to ensure that the boundary conditions between primitives are consistent. This modification, called constrained fitting, is necessary, for instance, when two different primitives are tangent [19]. It has also been shown that blends at the intersections can be determined with relatively few touch points close to the intersections [20].

B. Exploration strategy

An original strategy is proposed, which is well suited for the tactile exploration of rough and constrained environments such as oil wells. It is based on the collection of single probe points over large surface areas, intelligently selecting these points based on the partial interpretation of the surface being discovered.

The use of discretely probed points, as opposed to a continuous track of the robot tip along the surface, is chosen for two reasons. First, oil-wells surfaces are rough and sometimes covered with a thick and highly viscous material called mud cake: this prevents the use of a continuous tracking strategy. Secondly, measurements present noise, and primitives may be locally deformed; therefore inferring a primitive from a small local region is intrinsically unreliable, even if many data points are used. In fact, simulations show that a reliable primitive fit requires a long path, made of hundreds of such points if these are taken consecutively along a continuous path (as confirmed by [9]), while only a dozen points are sufficient if they are sparse and well separated.

The guidance of the robot based on the continuous interpretation of sequentially-acquired data is a key factor for an efficient tactile mapping. An exhaustive search, where points are probed in a fine grid, will be prohibitively time consuming. To map the environment with a shorter end effector path, and therefore in shorter time, a technique called the Best Cone search has been developed. The concept is to move the robot so that each measurement gives the most information, as follows:

1. The robot starts in a random direction.
2. It sequentially probes (see below) a surface until a primitive is identified to a desired accuracy.
3. Then, the robot chooses another direction (as discussed below), and moves along a line until it touches a new point.
4. If this point belongs to a known primitive, it will move elsewhere as in (3), otherwise it will investigate and identify the surface, as in (2), before continuing the search in a new direction.

Step (2), called Uniform Surface Density (USD) search, is a new strategy that probes points sequentially, one close to the other, on the same surface. The arrangement of these points has the objective of minimizing what is called dispersion, the radius of the largest ball that does not contain points. On a two-dimensional surface, dispersion is proved to be minimized when points are disposed on a lattice of equilateral triangles (cf. [21] for formal definitions). The robot tries to reproduce this lattice structure on the unknown surface (Figure 3), simply moving its tip on circular paths equidistant to two probed points until it touches the surface.

Step (3) is critical to the method. The new direction is chosen to maximize the expected amount of information given by the next measurement. This approach has been studied in SLAM literature, cf. [22] [23], and it resembles the problem called Next Best View in computer vision [24] [25]. In this work, a simple geometric method is proposed. This new method has no proof of optimality but it performs very well in simulations and experiments, with different shapes.

Conceptually, like a man who looks around and chooses to explore where he has not yet been, the robot chooses to move along the direction that is away from all
previously touched points. To do this, it computes all the possible circular cones with vertex at the end effector \( P_{ee} \) and subject to the constraint that all the probed points \( P_i \) are external to the cone (Figure 3). Among these cones, the one with biggest aperture angle is chosen, and its axis \( N \) is the next exploration direction:

\[
\tilde{N} = \arg \max_N \left\{ \min_i \left( N \cdot \frac{P_{ee} - P_i}{\| P_{ee} - P_i \|} \right) \right\}
\]

The internal minimization determines, for a given direction \( N \), the largest cone aperture angle that does not include any touch point. The external maximization chooses \( N \) to maximize this angle. This evaluation is computationally fast, because it involves a search in just the variables representing the cone axis. The primitives do not affect the choice. In some applications, the intersections between primitives are important regions and require more accuracy, which can be achieved with detailed exploration along these intersections after the initial identification.

III. SIMULATIONS

The effectiveness of the algorithms has been evaluated in two environments, the oil well junction and a generic shape composed of a sphere, a cylinder and a plane (Figure 4). This shape, although very simple, possesses different primitives, requires constrained fitting between the cylinder and the sphere, and presents a sharp intersection. Shapes used in these simulations are ideal, but the measurements are corrupted by random Gaussian noise with 1 mm standard deviation. The robot tip moves inside the environment, constrained by the surface and by its workspace limits. The robot has no initial knowledge of the shape to map. When it comes in contact with the surface, the contact point is saved and the robot moves somewhere else. The exploration terminates when the environment is identified (within 1% of the correct dimensions).

In order to provide a comparison for the Best Cone search, four strategies have been implemented and tested:

1. Uniform Surface Density (USD) search: it consists in the iteration of step (2) of the Best Cone strategy, without ever changing direction. It is designed to uniformly map the whole environment with a certain density.
2. Random search: Every time the robot touches a point, it then moves in a random direction.
3. Best Cone search: Described in the previous section.
4. Semi-random search: Like in the Best Cone strategy, USD is locally used to identify primitives. However, once a primitive has been identified, the new direction is selected randomly.

For each strategy and environment, 20 simulation trials were run. The means and standard deviations of the end-effector path lengths are shown in Figure 5. The results show that for both environments the Best Cone strategy has the best performance.

To be practical, a mapping procedure needs to be sufficiently robust to identify shapes that are not ideal primitives. The Best Cone strategy has been tested on irregular surfaces where increasing random variations are added to the surface. The algorithm always converges to the correct primitives in all the trials when the noise (\( \sigma \)) is within 2% of the cylinder radius, a rather large variation. The average number of points does increase with increasing variation from 39 with 0.1% \( \sigma \) variation, to 51 points with 1% \( \sigma \) and 59 points with 2% \( \sigma \). With higher values of \( \sigma \), the fitting and segmentation procedure convergence is not always assured.

To study the effect of geometric non-idealities on the methodology, the cylinder in the generic environment is given an elliptical cross section. The Best Cone algorithm still proves effective when the eccentricity is not extreme. For example, with eccentricity 0.5 (i.e. major and minor axes are 107% and 93% of the original radius), the elliptical cylinder is identified for 90% of the time as a cylinder. The algorithm is not given an elliptical cross section cylinder as a primitive.

IV. EXPERIMENTS

A. System Description

A laboratory system was designed [26] to test the algorithms developed in this work, see Figure 6.
experimental system represents the size and kinematic configuration of a well junction field system, given the constraints of the laboratory. The environment tank is designed to represent a scaled version of an oil well junction for simulation and testing purposes.

The manipulator is controlled by a simple impedance controller scheme [12]. Therefore, no force-torque or tactile sensor needs to be mounted. This is a key element of the field design, since building a force-torque sensor that can function in the very hostile down-hole environment would be difficult and prohibitively expensive.

Since the robot base is assumed fixed with respect to the surface being explored, in the field system the robot will be mounted on a cylindrical tool module that is lowered into the well. This tool module will bind itself to the well bore above the junction using expanding rubber mounts. Typical main and lateral bores in well junction measure 23 cm and 18 cm in diameter, with a divergence angle of 5°. This junction would be approximately 203 cm long. The full exploration of this long and narrow junction space requires a redundant manipulator. A 4 degree-of-freedom (DOF) mechanism consisting of a 3 DOF anthropomorphic arm attached to a long prismatic link aligned with the axis of the main well bore is well suited. For simplicity, in this experimental system only the 3 DOF arm has been implemented, replacing the first prismatic joint with a mounting ring that can be fixed at different heights. The sizing of the arm links is based on of the workspace size and dexterity requirement inside of an oil well. The manipulator links have lengths of 20.32 cm and 15.24 cm, see Figure 7. The links are stiff enough so that link deformations introduce negligible error in the measured position of the probe tip.

Each joint assembly consists of a motor, gear train, encoder, and associated support bearings. Brushed DC motors are used. The joints are compact in order to minimize the potential for undesirable contact between the manipulator elbow and environment. The joints are sealed by encasing them within rubber bellows to protect them from drilling mud used in oil wells. The manipulator has been used to test the system and the control approach while submerged in fluids: water, simulating properties of some lower-density oil well fluids, and sucrose solutions with different concentrations, simulating more viscous and dense well fluids [27].

B. Experimental Results

Using the experimental system, a set of preliminary experiments has been completed. The manipulator performance has been characterized and several search methods have been studied. With an appropriate backlash compensation method, the manipulator provides sensing errors of roughly 1 mm.

Figure 8 shows a comparison between the pattern of experimental touch points produced by the USD and the Best Cone strategies. The robot has no a-priori knowledge of the environment or the kind of primitives involved, but the search is terminated when the algorithm converges to two cylinders with radius within 2% of the real value. Figure 8 also shows the primitives fit to these touch points as well as the intersection. Table 1 summarizes the results for these two strategies and the semi-random search.

Using the USD search, the manipulator needed to travel 8.1 m to make these measurements over a period of 311 s. The semi-random search presented similar results. The Best Cone strategy led to better performance: the number of points was reduced to 29 and the total distance traveled was reduced by half. Similarly, the required time was reduced to 180 s. Figure 8 clearly shows the reduction on the number of touch points using the Best Cone strategy.

The preliminary experimental results obtained to date suggest that the proposed algorithms for the tactile exploration of unknown environments are feasible, and an appropriate exploration strategy greatly reduces the necessary time.

<table>
<thead>
<tr>
<th>Method</th>
<th>Number of points</th>
<th>Distance traveled [m]</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>USD</td>
<td>68</td>
<td>8.1</td>
<td>311</td>
</tr>
<tr>
<td>Best Cone</td>
<td>29</td>
<td>4.5</td>
<td>180</td>
</tr>
<tr>
<td>Semi-random</td>
<td>67</td>
<td>8.9</td>
<td>382</td>
</tr>
</tbody>
</table>
The new approaches are tested in simulations and laboratory processing methods are developed to overcome this limitation. Is, in many cases, very sparse. Here data search and data challenge in this concept is that the data from such exploration where conventional range information is not feasible. A key of using manipulator based tactile exploration of environments the structure of deep-hole oil wells, and in particular mapping the junctions where divergent lateral bores intersect the main bore. This work proposes an original search method for tactile exploration, based on the intelligent selection of touch points, and on the representation of the surface as simple geometric primitives. This method only requires a manipulator provided with joint encoders, and no force or tactile sensor. Simulations and laboratory experiments show that this method is feasible and effective for tactile exploration, in terms of time, traveled distance and data points needed to map the unknown surface. Challenging issues of mechanical design presented by the very hostile down-hole environment remain to be addressed.

V. CONCLUSIONS

The objective of this research is to evaluate the feasibility of using manipulator based tactile exploration of environments where conventional range information is not feasible. A key challenge in this concept is that the data from such exploration is, in many cases, very sparse. Here data search and data processing methods are developed to overcome this limitation. The new approaches are tested in simulations and laboratory experiments in the economically important context of mapping the structure of deep-hole oil wells, and in particular mapping the junctions where divergent lateral bores intersect the main bore. This work proposes an original search method for tactile exploration, based on the intelligent selection of touch points, and on the representation of the surface as simple geometric primitives. This method only requires a manipulator provided with joint encoders, and no force or tactile sensor. Simulations and laboratory experiments show that this method is feasible and effective for tactile exploration, in terms of time, traveled distance and data points needed to map the unknown surface. Challenging issues of mechanical design presented by the very hostile down-hole environment remain to be addressed.

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