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IMPROVED STRATIFIED CONTROL FOR HEXAPOD ROBOTS AND OBJECT MANIPULATION WITH FINGER RELOCATION

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Abstract

The paper deals with the motion design of legged robots and dextrous hands. We show the possibilities and limitation of conventional stratified control approach through the relative simple example of hexapod robot and offer some proposals for a more robust motion planning solution. The precision of the algorithms was improved by step length modification and the applicability was increased by time scaling. The developed software is based on symbolic computation. On the other hand, our fundamental goal is to provide a powerful basic concept for object manipulation with finger relocation in the context of stratified control as an extension of earlier works. The concept focuses on the finger gaiting manipulation (based on finger relocation) to gain some attributes of the nonsmooth object.

Keywords: stratified control, motion planning, hexapod robot, finger relocation.

1. Introduction

In the common sense, the intention of a manipulation task is to find a motion of the agents that move the object from a given initial grasp to the desired configuration. Several possible approaches of the essential mechanics of manipulating objects are investigated in [8]. On the side of control aspect, the most of manipulation systems overlay discontinuous equations of motion which forces particular nonlinear control methods. A new approach on this area is the stratified control [1]. Our immediate objective is to exhibit the stratified control approaches on the example of hexapod robotics system, point out its advantages and disadvantages and extend the earlier concepts for practical manipulation problems which obtain the most important attributes while the object is manipulated.

Section 2. deals with a general introduction to motion planning [5] due to LAFFERRIERE and SUSSMANN based on the foundation of smooth control theory (see [2], [3] and [4]). The systems having discontinuous equations of motion require more sophisticated algorithms. In this case, the configuration space contains several smooth submanifolds (strata). Section 3. is devoted to the theory of stratified motion planning problem (see [1], [7]). Section 4. describes the software implementation and improvements to motion planning algorithm and the application for hexapod robot. Section 5. proposes a concept for finger relocation regarding nonsmooth object to overcome the difficulties of stratified motion planning. We assume "point contact with friction" contact model and try to gain attributes of object meanwhile the (grasped) object moves along a trajectory.

2. Smooth Motion Planning

Based on the fundamentals of smooth nonlinear control ([2], [3], [4]) we present a method originated to Lafferiere and Sussmann ([5], [6]) for smooth motion planning problem (MPP). If we want to solve the MPP then our goal is to find a control in the configuration space that steers the starting point p to the end point q.

Definition 1 A *Nilpotent Lie algebra* with order k is defined by Lie algebra L where all the Lie brackets $[v_1, [v_2, [v_3, \ldots, [v_k, v_{k+1}] \ldots]]]$ equal zero.

Definition 2 The system Σ is said to be *nilpotent* if its controllability Lie algebra $L(f)$ is a nilpotent Lie algebra.

We assume that

1. The control system has no drift, i.e. $\Sigma : \dot{x} = u_1 f_1(x) + \ldots + u_m f_m(x)$.
2. $f = \{f_1, \ldots, f_m\}$ are *real analytic* vector fields on $\mathbb{R}^n$.
3. Σ is completely controllable.

Remark 1 It is worth remarking that the precise model of a finger should be added as a dynamics leading to system with drift.

The strategy. The proposal in [5] is to extend the system Σ to

$$\Sigma_e : \dot{x} = v_1 f_1(x) + \ldots + v_m f_m(x) + v_{m+1} f_{m+1}(x) + \ldots + v_r f_r(x)$$

where vector fields $f_{m+1}, \ldots, f_r$ are defined by higher order Lie brackets of the f_i selected so that $\text{span}\{f_{m+1}(x), \ldots, f_r(x)\} = \mathbb{R}^n$. The strategy consists of two main steps: at first, find a control v that steers the extended system Σ_e from p to q. Since the vector fields of Σ_e span the whole configuration space, the simplest case for smooth system is the straight-line segment. In the second step, we compute a control u for original system Σ that substitutes the fictitious control v. This step consists of additional steps. At the first time, one has to obtain the Philip Hall basis and the order of system nilpotency. Then, we can solve a formal differential equation in P. Hall coordinates on a special nilpotent Lie group. Finally, we achieve the control u from the P. Hall coordinates which is a set of Lie brackets where the "order of right hand side of Lie brackets" is equal to or greater than the order of left hand side.

Corollary 1 A basis B' of Lie algebra $L(X_1, \ldots, X_m)$ can be immediately obtained from a Philip Hall basis of $L(X_1, \ldots, X_m)$. Furthermore, the set $\{M \in B' : \text{degree}(M) \le k\}$ represents a basis of L_k^m where L_k^m is a free nilpotent Lie algebra in $(X_1, \ldots, X_m)$ with order k.

Definition 3 $\hat{G}(X_1, \ldots, X_m) = \{e^Z : Z \in \hat{L}_k(X_1, \ldots, X_m)\}$ is said to be a *Lie group with m infinitesimal generators*.

Definition 4 $G_k^m = \{e^Z : Z \in L_k(X_1, \ldots, X_m)\}$ is said to be the *free nilpotent Lie group of order k with m infinitesimal generators.*

Corollary 2 If $B_1, B_2, \ldots, B_m$ are a P. Hall basis of the Lie algebra $L_k(X_1, \ldots, X_m)$ then any $S \in G_k(X_1, \ldots, X_m) \equiv G_k^m$ can be expressed in the forms $S = e^{h_s B_s} e^{h_{s-1} B_{s-1}}, \ldots, e^{h_1 B_1}$, $S = e^{\tilde{h}_1 B_1}, \ldots, e^{\tilde{h}_{s-1} B_{s-1}}, e^{\tilde{h}_s B_s}$ where h_i is called *backward P. Hall coordinates* and $\tilde{h}_i$ is called *forward P. Hall coordinates*.

At this point, our goal is to find appropriate $a(t)$ for the desired trajectory in the form $x(t) = \bar{x} e^{a_1(x) f_1} e^{a_2(x) f_2} e^{a_3(x) f_3}$ such that the function $x(t)$ let give a solution for the formal extended differential equation

$$\begin{aligned} \Sigma_{fe}\colon \dot{S}(t) = S(t)(&v_1 f_1(x) + \ldots + v_m f_m(x) \\ &+ v_{m+1} f_{m+1}(x) + \ldots + v_r f_r(x)), \quad S(0) = 1 \end{aligned} \tag{1}$$

and obtain the needed control u based on P. Hall coordinates.

Remark 2 If the system is nilpotent then the additional inputs v expressed in P. Hall coordinates can be precisely composed of the original input u. If the system is not nilpotent then the solution will be an approximation.

3. Stratified Nonlinear Control Systems

If the system has discontinuous equations of motion then the configuration space cannot be described by one smooth manifold. The different types of constraints decompose the configuration space into smooth manifolds (strata) on which different smooth systems are defined. The works [1], [4] deal with the definition of stratified systems in detail. The theory investigates the problem when the system moves between strata where one of the strata contains the other one.

Definition 5 A set $\aleph \in \mathbb{R}^n$ defined by union of smooth manifolds (i.e. strata) is said to be *a regularly stratified set*.

Definition 6 The system is *stratified* if its configuration space is defined by stratified sets.

It is helpful to introduce some further notations and illustrate a notion on the example of two cooperating robots or two finger-tips (see *Fig. 1*). Denote $M \equiv S_0$ the whole configuration space. Let the stratum $S_i \subset M$ be a codimension one submanifold where only the ith finger is in contact with the object. Denote $S_{ij} = S_i \cap S_j$ where both the ith finger and jth finger are in contact with the object. Recursively, we can define $S_I = S_{i_1 i_2 \dots i_k} = S_{i_1} \cap S_{i_2} \cap \cdots S_{i_k}$ where $I = i_1 i_2 \dots i_k$ is a multi-index . The stratum with lowest dimension which includes the point x is said to be the *bottom stratum*. In the comparison of two strata, the *lower stratum* has by definition lower dimension than the higher stratum.

Theorem 1 *(Distribution approach for stratified controllability.) If there exists a nested sequence of strata $x_0 \in S_p \subset S_{p-1} \subset \cdots \subset S_1 \subset S_0$, such that the connected involutive closure of distributions (of strata) fulfills $\sum_{j=0}^{p} \bar{\Delta}_{S_j} |_{x_0} = T_{x_0} M$ then the system is locally stratified controllable from x_0, where $T_{x_0} M$ is the tangent space of M in x_0.*

The idea of stratified control is to find a common space where all the vector fields on different strata can be considered. It will be the bottom stratum. As an example, consider a manipulation system with two fingers and a plane surface. *Fig. 1* shows the configuration space and a manipulation as a sequence of flows where vector field $g_{1,1}$ moves the system off of S_{12} onto S_1 ("finger 2" disconnects the object), vector field $g_{2,1}$ moves the system off of S_{12} onto S_2 ("finger 1" disconnects the object), $g_{1,2}$ is defined on stratum S_1, $g_{2,2}$ is defined on stratum S_2 and keeps the system within them. Although we speak about object and fingers, the model can be applied also for legged robots and other mobile agents. In the case of a hexapod robot, the state (x) consists of the position and orientation of the reference point of the hexapod robot (x, y, θ), the angles of the leg groups (ϕ_1, ϕ_2) and the heights of the leg groups (h_1, h_2). The lower indices of S denote which leg groups are in contact with the terrain. The first index of g identifies the stratum in which the motion is performed. If the second index of g is 1 then there is a switch between two strata, otherwise not. Negative sign denotes inverse motion. For example, leg group 2 leaves the terrain $(g_{1,1})$, moves forward in the air $(g_{1,2})$ and returns to the terrain $(-g_{1,1})$. We distinguish two sets of vector fields.

Definition 7 A vector field is said to be a *moving off* vector field if it influences the contact between the finger and the object. On the contrary, a vector field is said to be a *moving on* vector field if it does not leave the actual stratum.

If the moving on vector fields commute with moving off vector fields then the flow sequence can be rearranged and reduced to bottom stratum. Furthermore, if the moving on vector fields in the higher strata are also tangent to the bottom stratum S_{12} then the two sequences achieve the same motion in the configuration space.

Remark 3 If a vector field on higher stratum (for example $g_{1,2}$) is not tangent to "its" substratum then it is possible to modify this vector field favourably.

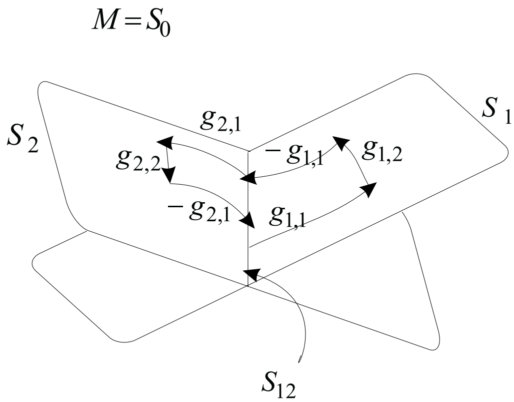

Fig. 1. Flow sequences in stratified configuration space.

Corollary 3 In general, if all vector fields that detach the fingers from the object are decoupled from all vector fields defined on the substratum and higher strata (i.e. their Lie brackets are zero) then the moving between higher and lower strata is possible.

However, we use a stronger assumption stated in the following.

Assumption 1 Assume that the tangent vector $\{\frac{\partial}{\partial h_i}\}$ can be produced as a linear combination of control inputs where h_i is the distance between the ith finger and the object. Additionally, assume that the effective equations of motion in a stratum are not influenced by the distance of the "contact free" finger.

The assumption guarantees that the Lie brackets between the vector fields obtaining the finger distance and any other vector fields are zeros (commutation).

Furthermore, since the "other" vector fields (i.e. the vector fields which do not influence distances between fingers and object) do not separate the fingers from the object, they keep the system in the substratum (if the starting point lies there) and the tangency requirements will be automatically satisfied. For stratified motion planning problem, we have to create the extended system on the bottom stratum (as a common space). At the first time, one takes set of vector fields in different strata and takes them into a *bottom stratified system* with the consideration of above assumption. After this, one can define the *bottom stratified extended system* with the Lie brackets among all vector fields of bottom stratified system.

Example 1 (Multiple Stratified System)

$$\begin{aligned} S_0\colon \dot{x} &= g_{0,1}u^{0,1} + \cdots + g_{0,n_0}u_{0,n_0} \\ S_1\colon \dot{x} &= g_{1,1}u^{1,1} + \cdots + g_{1,n_1}u_{1,n_1} \\ &\vdots \\ S_I\colon \dot{x} &= g_{I,1}u^{I,1} + \cdots + g_{I,n_I}u_{I,n_I} \end{aligned}$$

Example 2 (Bottom Stratified System)

$$\begin{aligned} \dot{x} = {} & g_{0,1}u^{0,1} + \cdots + g_{0,n_0}u_{0,n_0} \\ & + g_{1,1}\,|_{S_0}\, u^{1,1} + \cdots + g_{1,n_1}\,|_{S_0}\, u_{1,n_1} \\ & + g_{I,1}\,|_{S_0}\, u^{I,1} + \cdots + g_{I,n_I}\,|_{S_0}\, u_{I,n_I}, \end{aligned}$$

where the notation $|_{S_0}$ refers to the vector fields which take a part in bottom stratified system, however, they are defined originally not in this stratum.

Example 3 (Bottom Stratified Extended System)

$$\begin{aligned} \dot{x} = {} & g_{0,1}u^{0,1} + \cdots + g_{0,n_0}u_{0,n_0} \\ & + g_{1,1}\,|_{S_0}\, u^{1,1} + \cdots + g_{1,n_1}\,|_{S_0}\, u_{1,n_1} \\ & + g_{I,1}\,|_{S_0}\, u^{I,1} + \cdots + g_{I,n_I}\,|_{S_0}\, u_{I,n_I} \\ & + \text{Lie brackets}, \end{aligned}$$

where the term "+ Lie brackets" contains all the Lie brackets among the vector fields of the bottom stratified system. This stratified extended system is the starting point of the standard trajectory planning.

4. Software Implementation and Improvements to the Motion Planning Algorithm

The motion design consists of the following steps:

1. Definition of the representative points of the trajectory.

2. Creation of the bottom stratified extended system belonging to the motion problem.

3. Solution of the smooth motion planning on the bottom stratified extended system in the actual subsegment which consists of the following subsets: i) symbolic computation of the P. Hall basis, ii) symbolic computation of the P. Hall coordinates based on the vector fields of the problem and the P. Hall

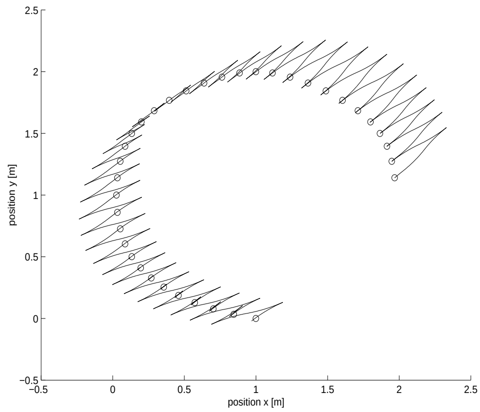

Fig. 2. Stratified motion planning for hexapod robot with constant orientation. The "o" denotes the described points.

basis, iii) symbolic computation of the solution of the formal differential equation, iv) numerical evaluation of the symbolic solution of the differential equation.

4. Numerical evaluation of the control and the flow sequences along the vector fields based on the solution of formal differential equation. Performing the time scaling.

5. Decision about the insertion of the moving off vector fields between two flows if necassary.

6. Simulation within the actual subsegment and distance correction.

7. Jump to *3.* if the last segment is not reached yet.

In the following, we demonstrate the stratified control on a hexapod robot and provide some improving proposals to the original method of LAFFERRIERE and SUSSMANN [5] which can also be used for the more complex manipulation problems. The results for hexapod robot with two different prescribed orientations are illustrated in *Figs. 2* and *3*. The figures show the motion of the reference point of the hexapod robot. It can be seen that the results show good accuracies although the trajectories between two points of a segment have quite different characteristic. Obviously, a tangent orientation in a point causes smaller difficulty for a motion planning algorithm than constant orientation. The major problem of the methods is the choice of the length of a subsegment. There exists critical distance between the end points (more details in [5]) which assures the convergence, however, its estimation arises to a hard question without theoretical answers. We give here a proposal for the problem. This algorithm starts with an initial distance D_1 between

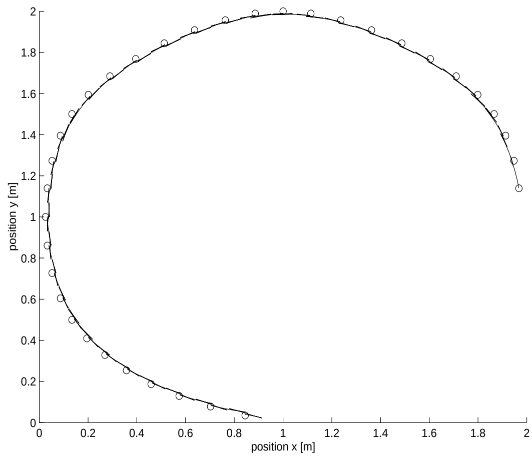

Fig. 3. Stratified motion planning for hexapod robot with tangent orientation. The "o" denotes the described points.

p_1 and q_1. If the $\|q_i - p_i\| > D_{i-1}$ (where $p_i = q_{i-1}$) then let $D_i = D_{i-1}/2$ and insert some additional points between q_i and p_i through a line segment. If $\|q_i - p_i\| < D_{i-1}/2$ then restore $D_i = 2D_{i-1}$. The results with and without this algorithm are sketched in *Figs. 5* and *4*. The improvement does not assure the convergence in each step but it avoids the convegence problem for trajectories consisting many described points, prevents the error accumulation and keeps D_i in the near critical distance D_r for long time.

The original motion planning method returns with definite time for the trajectory (computed time). In the implementation, we applied a time-scaling which enables to prescribe arbitrary time point to each configuration point. The idea is to introduce a factor for each input in the actual subsegment which is obtained with the quotient of the desired and computed time for the actual subsegment.

5. Improved Conception for Object Manipulation with Finger Relocation

The (smooth and stratified) motion plannings for manipulation have a number of limitations. The earlier methods based on stratified method such as [1], [7] care for object of special geometry. We consider in our concept a more general class of the objects having not exclusively smooth surfaces. The key idea is to decompose the surface of object into smooth submanifolds in the configuration space. Consider an object with two (smooth) surfaces (i.e. with edges) as an example.

Denote the subscripts of strata S the fingers which are in contact with the object and related to this, indicate the superscripts of S the surfaces which are in contact with the corresponding fingers. Based on this convention, *Fig. 6* illustrates

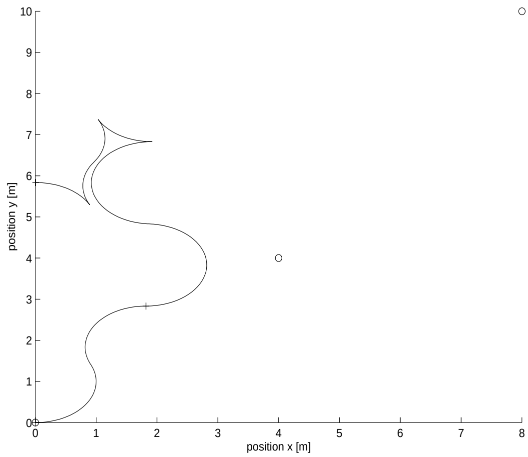

Fig. 4. Stratified motion planning without improvement. The "o" denotes the described points, the "+" denotes the reached points.

the problem of stair climbing with fingers. The figure shows the strata and the flows but not the real stair. Dotted lines illustrate the heights which should be overstepped by the lifted fingers. In the beginning, both the fingers contact the "surface 1" (i.e. the ground) then the "finger 2" moves from the ground to the stair (i.e. to "surface 2") and after this, the "finger 1" moves also from the ground to stair. One cannot apply a pure stratified control method for the illustrated example because the union of bottom strata S_{12}^{11} and S_{12}^{22} on which the bottom stratified extended system is defined, is not smooth. Our applied concept uses the proposals of [9]. We define two foliations on the total configuration space. The foliation of "palm" variables (P_0) is associated to the position and orientation of palm frame and the foliation of manipulation variables (S_0) is associated to the internal shape variables and to the position and orientation of object in the palm frame. This kind of position and orientatiton will be called group variables. We restrict our attention mainly to the foliation of manipulation meanwhile palm frame is in calm. Indeed, the configuration subspace of manipulation variables is in itself a stratified configuration space (with strata S_0, S_1, S_2, S_{12} etc. where constraints are defined with the finger contacts). The idea is to separate the two configuration subspaces in point of view of manipulation problem.

The proposed concept will be demonstrated for two fingers (agents) climbing a stair which can be considered as the simple model of finger relocation on a nonsmooth object.

Step 1.) Move the object to (advantageous) manipulation position and orientation through the change of coordinates of palm frame while all fingers are in

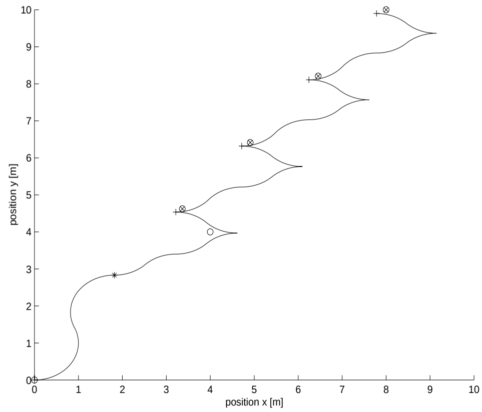

Fig. 5. Stratified motion planning with improvement. The "o" denotes the described points, the "+" denotes the reached points. The "*" denotes the additional inserted points.

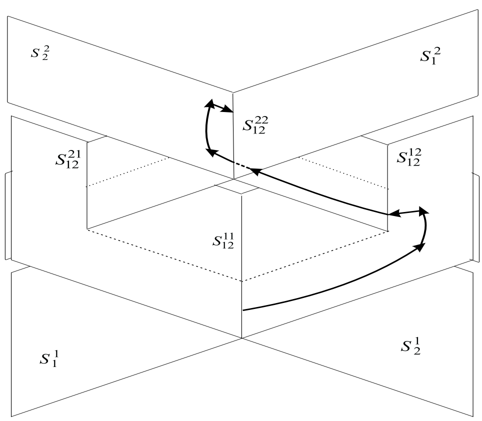

Fig. 6. Flow sequences of stair climbing in configuration space.

contact. Meanwhile, we measure the finger-tip contact forces and try to obtain informations and properties of the object. In this case, we perform a conventional motion planning in the configuration subspaces associated to palm variables. The trajectory can be determined by forward Philip Hall coordinates in the form $S = e^{\tilde{h}_1 B_1}, \ldots, e^{\tilde{h}_{s-1} B_{s-1}}, e^{\tilde{h}_s B_s}$ which can be regarded as a solution of formal differential equation $\Sigma_{fe}: \quad \dot{S}(t) = S(t)(v_1 f_1(x) + \ldots + v_m f_m(x) + v_{m+1} f_{m+1}(x) + \ldots + v_r f_r(x))$ with the initial condition $S(0) = 1$. It is worth remarking that the complete controllability is usually not guaranteed, i.e. the controllability Lie algebra generated by vector fields $f = \{f_1, \ldots, f_m\}$ of hand does not satisfy the *Lie Algebra Rank Condition* (LARC) [6] which restricts the reachable set from starting point. We assume that the force closure stability is hold along the trajectory [7].

Step 2.) Perform an agent relocation. The agent relocation is based on *stratified* motion planning in the bottom stratum of configuration space S_0 of manipulation variables. (In the example, the bottom strata S_{12}^{11},S_{12}^{12}, S_{12}^{21} and S_{12}^{22} play important role in this respect.) Indeed, this is a finger gaiting where the stages before and after a disconnection between ith finger and object (while all the $m-1$ other fingers are in contact) corresponds the constraints $d\Phi_j\{g_{j,1}(x)u^{j,1} + \cdots + g_{j,n_j}(x)u^{j,n_j}\} = 0,\ j = 1\ldots m$ and $d\Phi_j\{g_{j,1}(x)u^{j,1} + \cdots + g_{j,n_j}(x)u^{j,n_j}\} = 0,\ j = 1\ldots m, j \neq i$ respectively. Φ_j are the level functions of strata S_j (for example the height of the fingers in the stratum). First time, we relocate the fingers only their on own smooth surfaces i.e. the start and end points of each finger are in the same smooth surface (but this may be different for different fingers). It means that we take all the interesting trajectories which go through all the important contact points while each finger remains on its own smooth surface. In fact, it is a "scanning" in the sense that the relevant (contact) points of the trajectories should play a distinguished role in point of view of attributes of the object. If the scanning finished then continue with next Step else repeat this step taking extra relevant contact points on the surfaces of the corresponding fingers for identification purposes.

Step 3.) Relocate a finger from the surface to a new smooth surface.
In this phase of motion planning, the initial and final point lay in different bottom strata. Our goal is to perform a motion planning between the two bottom strata. The main difficulty is that the union of the two bottom strata is not smooth. They are connected via a *common stratum* with higher dimension. To illustrate the problem, place the "finger 2" from the ground onto the stair corresponding to the example of stair climbing. Then our goal is to steer the system through S_1^1 from S_{12}^{11} to S_{12}^{12}. Since the trajectory between the start point (in S_{12}^{11}) and end points (in S_{12}^{12})lay in the same stratum (S_1^1), this is a smooth motion planning problem where the system is defined by the vector fields of S_1^1. If the vector fields in the higher stratum do not satisfy the LARC then the solution of motion planning problem is not guaranteed. One can use the idea of stratified approach where we consider this higher stratum S_1^1 as a "bottom stratum" of more higher strata which contain it. Since the proposal allows to apply additional vector fields, we gain a more robust solution. Of course

it may occur that the extended system on the common stratum is not controllable. However, we emphasize that in strict sense, one has to find only a path between the two smooth bottom strata and not exactly between the actual initial and final points. If the relocation meets difficulties, jump Step 5 else continue with next Step.

Step 4.) If we have not enough information about the object then jump Step 1 else go to final Step.

Step 5.) Two relevant cases can be distinguished:

- Object as obstacle. The obstacles indicate boundaries on the strata in configuration space (bounded by dot line in Figure 6). If the computed trajectory meets with the obstacle then a smaller step size is needed. If the finger cannot reach the target surface because of the geometry of the object then one must move another finger or design an additional manipulation (with sequence of more than one finger relocation) to avoid the obstacle.
- Collision during agent relocation. If the finger cannot avoid another finger during the process of relocation then the fingers may clash. In order to overcome this problem, one has to relocate more than one fingers at the same time. Another proposal may be to relocate the fingers in alternate way. The first idea is faster but requires multiple redundancy for force closure stability.

Depending on the strategy, the algorithm is carried on with Step 2 or 3.

Step 6.) End of algorithm.

6. Conclusions

Stratified control is a promising method for nonlinear systems having discontinuous equations of motion. The main disadvantage of earlier methods is the assumption of smooth objects and their limited applicability. We gave an algorithm for motion planning for legged robots and the finger relocation problem of dextrous hands. The precision of the algorithms was improved by step length modification and the applicability was increased by time scaling. The developed software is based on symbolic computation. Its effectiveness was illustrated by the motion planning of hexapod robot. A new concept was developed for nonsmooth object manipulation with finger relocation of dextrous hands whose software implementation is in progress.

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