Proceeding of the 2013
RSI/ISM International Conference on Robotics and Mechatronics
February 13-15, 2013, Tehran, Iran

A New Taxonomy of Robotic Regrasp Planning Approaches and Methods

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***Abstract*— In robotic manipulation, regrasping occurs when a robot's hand or gripper needs to change the orientation or gripping positions of an object successively until the desired configuration is reached. Planning of such movements is called Regrasp Planning, which is a challenging problem and has attracted the attention of many roboticists. After thoroughly studying the related literature and identifying major approaches and methods of regrasp planning, a new taxonomy was constructed that is presented in this paper. The novelty of the proposed taxonomy is in classifying a vast number of related researches into seven major approaches, each containing several specific methods, twenty in total. The taxonomy presents the whole literature in a unified hierarchy and provides brief descriptions for each approach and method in a way that researchers can use it to recognize existing strengths and gaps of the field and to conduct their own studies toward new directions.**

***Index Terms*—Regrasping, Regrasp Planning, Finger Gaiting, Sliding, Rolling, Pick and Place**

I. INTRODUCTION

Modern-day robots can be carefully hand-programmed to carry out many complex manipulation tasks, ranging from using tools to assemble complex machinery, to balancing a spinning top on the edge of a sword. Robotic grasping consists important manipulations which contribute greatly to the production quality, cycle time, and cost in manufacturing, assembly and other industrial fields.

When moving an object from an initial configuration to a goal configuration, a robotic gripper or hand may not be able to perform the task directly because of surrounding obstacles, kinematic or geometric limitations, or incompetent grasp configurations. Therefore, the robot will need to change the grasp configuration in intermediate stages, before the final configuration is reached, which gives rise to the notion of Regrasping and Regrasp Planning.

Depending on the kind of the end effector a robotic hand is equipped with, its grasp planning varies accordingly. For example, many existing works investigate multi-fingered hands since parallel jaws cannot perform in-hand manipulations which are necessary for efficient regrasping. In this paper a few fundamental approaches to Regrasp planning (such as Finger Gaiting, Pick and Place, Finger Sliding, etc.) are extracted from the literature. These general approaches are the essences of more specific methods which are also explained. Some methods utilize a combination of two approaches. Some of the mentioned approaches or methods had specific names, for which we have reported without modification, and some of them lacked a specific title, for which we selected keywords based on their employed concepts.

The paper is organized as follows: in sections II to VIII the major approaches and methods of regrasp planning are introduced and briefly described, and in section IX a new taxonomy is proposed which depicts the hierarchy of the methods. Conclusions come in section X.

II. FINGER GAITING

In this approach which is suitable for multi-fingered robotic hands, one or more fingers lift off the object while other fingers stay on the object without unfixing it or loosing force-closure. The detached fingers then rest on the object in new positions. The minimum number of fingers must be three: two fingers hold the object and the other manipulates or repositions it. Note that for multi-fingered hands at least two fingers are needed for holding the object, whereas for stable grasping at last three fingers are needed. Fig. 1 shows an example of finger gaiting, through which the object moves downward. We have identified six methods that are based on the finger gaiting approach, described as follows:

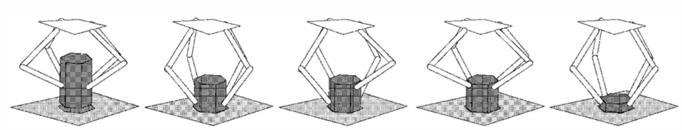

Fig. 1. An example of Finger Gaiting [13].

A. States Graph

This method creates primitives that involve rotation and pivoting. In the rotation-primitive the object rotates by serially exchanging the fingers around an axis perpendicular to the plane passing through the fingertips' contact points on the object. In the pivoting-primitive two fingers hold the object from opposite faces and the other fingers exert forces on the object to rotate it about the axis passing through the two contact points of the fingers that hold the object. Afterwards, based on those primitives a state graph (network) is created with nodes representing states of the object and edges between

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two nodes denoting possible primitives between two states. By finding a path in the graph the object moves from one configuration to another [1].

Another variant of the primitives-states network uses torque sensors in the fingertips and a distance sensor in the palm of the hand for avoiding or repairing poor grasps during the manipulation that may lead to undesirable motions or regrasping failures [2].

B. Hybrid Control-based

This method generates trajectory reference and hybrid control for fingers and utilizes three equations: one for describing continuous dynamics, one for discrete dynamics, and one for the system output. The system output is a hybrid vector consisting *p*-dimensional continuous and *r*-dimensional discrete outputs. In fact a duty of the hybrid system is to perceive the regrasping task that generates reference behavior models. In this method four phases (or states) are defined for lifting a finger from the object: Reduce, Move, Increase and Stable, which represent the sequence of decreasing the force exerted by the finger until detaching from the object, moving the finger along a specified trajectory, increasing its force on the object at a new position, and finally stabilizing there. During in these phases other fingers must maintain their stable contacts and grasp configurations [3, 4].

C. Optimization-based

This method uses force optimization and impact control in regrasping tasks for finger gaiting and stably holding an object without impacting or displacing it. When a finger moves off the object, other fingers should grasp it by exerting optimized forces. By this method it is possible to determine normal wrench vectors of the remaining fingers and find a set of wrench balances that keeps contact force vectors positive toward the object's surface and with directions lying within the Coulomb friction cone. This can be applied by a recursive algorithm [5].

In addition to wrenches, the optimization-based method also contains hand pre-shaping optimization for regrasping procedures. In this variant, the hand shape is repeatedly modified using an optimization algorithm like GAs. Two equations are required: one for divergence of fingertips and one for curling of each finger. Assuming that each finger (containing links and joints) passes through a distinct plane, when it is lifted off the object, an optimal pre-shaping is calculated which enables easy repositioning of the finger in a way that no contact with the object occurs during the procedure. The pre-shaping increases the grasping stability of the remaining fingers and facilitates the detachment of other fingers after the free finger reattaches to the object [6].

Another optimization-based method is proposed in [7] which utilizes the GAs to minimize changes in the object's successive orientations (thus securing a stable grasping) when a finger must be detached from the object due to its joint limits and replaced by a redundant finger.

While many finger gaiting methods based on predefined regrasping cannot be applied to objects with different sizes, the Evolutional Programing (EP) algorithm was employed in [8–11] to find new locations for fingers within their joint limits. This method generates regrasping movements by determining detach-move-reattach motions of fingers and adjusts these movements according to the object's size and occurred positioning errors. When a lifted-off finger intends to attach to a planned new location, it may miss the exact point, and this error can be accumulated during the whole regrasping operation. The EP proposes adjusted motion directions for the fingers such that the planned ultimate position is reached despite errors or variations in the object's size.

D. Sensor-based Error Correction

When the surface of an object has discontinuities (e.g. because of cavities or irregular edges), grasping errors might occur in finger gaiting. For example a finger may tumble in a hole and lose grasping stability or contact. These errors, however, can be compensated by employing sensor feedbacks. Sensor-based error correction has three steps: establishing contacts between fingertips and the grasped object, doing local parameterization of the object surface (for force, position, etc.) at new contact points, and finally verifying that the resulting grasp remains force-closure, which allows further regrasping operations by other fingers [12].

E. Primitives-based

In this method four primitive classes for regrasping operations are created, including (1) reorientation-regrasping, (2) rotation-regrasping, (3) displacement-regrasping, and (4) correction-regrasping, with each class having its solving strategy. Then an algorithm decomposes a desired object movement into consecutive sub-movements with primitive regrasping for each. Primitive regrasping consists of simple finger displacements while the object being held remains fixed [13].

F. Switching Graph

This method constructs a graph in which each node represents a group of relative force-closure grasps. A group is a combination of different non-overlapping (independent) regions of the object's surface such that fingers lying anywhere within the regions together form a force-closure grasp. Afterwards, the feasibility of finger-switching between a grasp configuration in one node and another grasp configuration in another node is checked. The whole regrasping operation is then planned by searching the graph. By taking advantage of independent contact regions, finger gaiting can be done between two different contact regions. Grasping will be force-closure when fingers lie in independent contact regions [14–17].

In a variant of this method the object's surface is tessellated in a way that the centroid of each tile is a contact point through which an internal normal vector passes. Regrasping is done only on these points; i.e., the fingers may attach to the object only on the centroids to form a force-closure grasp. A group of as many centroids as the number of fingers represents a node of a switching graph in case that fingers lying on centroids form a force-closure grasp. By changing the number of tiles or the method of tessellation, or by clustering the contact points the computational burden can be reduced [18, 19].

III. Finger Sliding

In this approach one ore more fingers slide on the object sequentially or simultaneously in a controlled manner. Fingers should have a trajectory on the object's surface and must hold a force-closure grasp during sliding (Fig. 2). This is important since by losing the force-closure the object may fall or move to undesirable configurations. Finger sliding on the object is performed under friction constraints. We have identified three methods that are based on this approach, as follows:

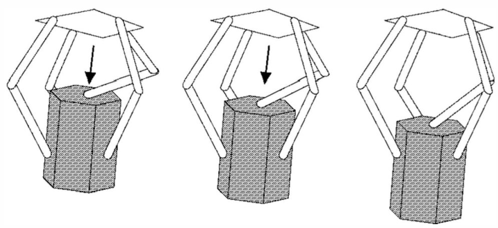

Fig. 2. An example of Finger Sliding [13].

A. Dynamic System

In this method first the dynamics of the fingers and the object are obtained based on the equations of the system. A hand system is consisted of two components: the object and the multi-jointed fingers that hold the object. A non-sliding contact is considered as a ball-and-socket joint and a sliding contact as a translational joint. These contact types are distinguished by friction constraints. By adjusting the internal forces the fingers can correctly slide to their new locations [20, 21].

B. Same-Facet Sliding

In this method that is used for 2.5-dimensional parallel grasping and is a combination of the Finger Sliding approach and the Switching Graph method, two grasps in one node of the switching graph can exchange through sliding. That is, as long as the fingers lie on facets (or sides, in 2D) of a polygonal object without exiting from the edges of their attached facets, they can maintain a force-closure grasp while sliding. For example, when a finger is on a facet and two fingers are on the opposite facet of the polygon, one of the two fingers can start sliding while by adjusting the forces of the other fingers a force-closure grasp can be maintained [16].

C. Surface Tessellation

In this method the object's surface is tessellated into discrete regions with a meshing that consists of independent contact areas (for assuring force-closure grasps) and un-graspable areas (for avoiding non-force-closure grasps). Such a division obviates the need for defining points precisely, and so the finger can slide on the surface with force-closure grasp [22, 23].

IV. Finger Rolling

In this approach fingertips roll on the object's surface to transfer it from one configuration to another. The geometrical shapes of the fingertips and the object are important since during the rolling the force-closure grasp must be maintained. This approach is usually used along with finger gaiting in order to resolve situations when gaiting fails to generate a solution. There are three methods based on this approach:

A. Moving on the Greatest Circle

This method has one condition for moving: finger rolling for a sphere-like object should be done on the greatest circle of the sphere. Moving of a contact point to another location on the sphere is decomposed to consecutive motions on meridians and the equator of the sphere. As a result any movement is always performed on the greatest circle [24].

B. Failure-based Analysis

This method is based on decomposing the motion of a point contact from one position to another into linear trajectories regardless of the object's shape, which are then converted to joint movements by a Jacobian matrix (Fig. 3). First a tentative trace of the current contact point toward a 'suspended' point (which selected randomly but is closer to the goal) is drawn on the object's surface and then extended further. Then another initial point is selected and this procedure continues until the goal is reached. For each point the conditions of stable or failing grasps are analyzed and the best path from the start to goal is determined by a heuristic method, which regulates the selection of suspended points and the amount of line extensions [25].

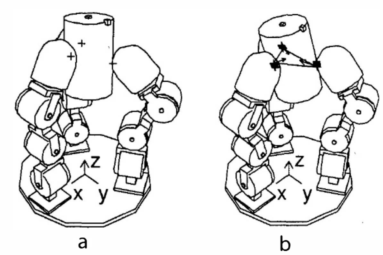

Fig. 3. An example of Finger Rolling: (a) initial, and (b) unstable grasps [25].

C. Sensor-based Rolling

In this method stable grasps are maintained using sensor feedbacks regardless of the objects' kinematics. Calculating the object's center of mass is very important since the contact points must be selected above the center of mass. Otherwise, the object will start to rotate about the axis that passes through the contact points [26].

V. Pick and Place

Another fundamental regrasping approach is placing the object in an intermediate situation (e.g. on a table surface) and then picking it up (Fig. 4). The Pick and Place approach is suitable for robots equipped with parallel-jaw end-effectors or hands that are unable to do in-hand manipulation because of joint limitations or large obstacles [27]. We have identified three methods that are based on this approach, described as follows:

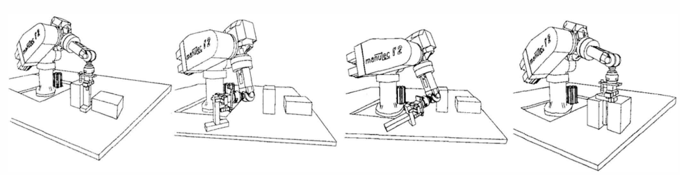

Fig. 4. An example of Pick and place [29].

A. Grasp-Placement-Grasp Triple

This method generates classes of grasping configurations and the object's stable states on the table surface, and then plans a regrasping operation by searching the space of compatible sequences of grasping and stable states using the breadth-first strategy. This space is consisted of grasp-placement-grasp triples. Construction of the classes (triples) is done offline whereas searching is performed online [28–30].

B. Lookup Table

This method increases the computational speed by initially evaluating and storing in a lookup table all feasible pick and place operations with respect to kinematic and geometric possibilities of the robot and the object (the processing stage). Then by having the initial and final configurations of the object and the robot, a sequence of mutually compatible and feasible grasps and stable placements on the table is extracted from the look up table (the planning stage). Since feasibility evaluations contains collision checking, path planning, and invers kinematics computations for all grasps, forming the look up table is very time consuming, and so the processing stage is done before the planning stage [31, 32].

C. Stable Planes

Another method for picking and placing by multi-fingered hands is to assume stable planes attached to those faces of the object that are in contact with any obstacle or the table surface. Planes attached to curved surfaces of the object have poor stability and should be removed from the object. Now the pick and place operation can be performed by moving the object from one stable plane to another [33].

VI. Bimanual Regrasping

Regrasping can also be done by two hands. In the bimanual approach the object which is initially grasped by a hand in its starting configuration is grasped by another hand and moved to a new configuration. This cycle is repeated until the final configuration is achieved (Fig. 5). In a variant of this approach developed for large objects, two hands of a humanoid robot grasp the object simultaneously, manipulate it and place it at an intermediate position, and then regrasp it. Three methods for Bimanual regrasping are described below.

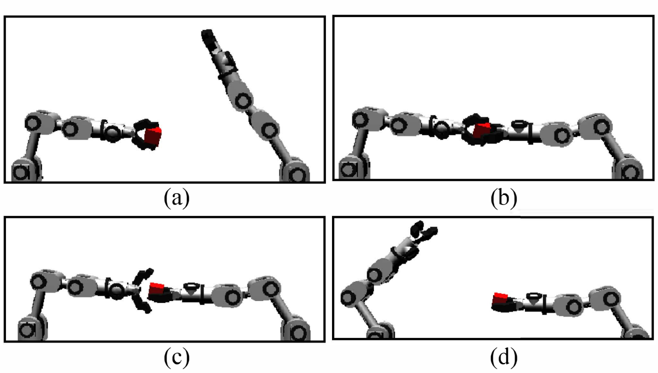

Fig. 5. Bimanual regrasping.

A. Multiple Roadmaps

This method is used for bimanual grasping of very large objects. First a 'manipulation' probabilistic roadmap (PRM) is constructed that connects the start to goal positions. The object moves on the roadmap until a narrow passage is encountered, after which a second 'regrasping' roadmap is constructed to find an alternative path toward a point in free space, from which a feasible path is found using another manipulation roadmap [34].

B. Simultaneous Grasping Score

In this method for bimanual regrasping of small objects, all possible configurations of grasping by each of the hands are analyzed and assigned a quality score based on involved forces, object stability, etc. Then different combinations of non-overlapping bimanual grasping (double-grasps) are considered and an aggregate quality score is allocated to each double-grasp state by summing the individual scores of each hand. Thus the most stable double-grasp can be identified and preformed, as a result of which one of the hands can move off the object [35].

C. Image Processing-based

In this recent method of bimanual regrasping, instead of planning the whole regrasping procedure *a priori*, the object is initially grasped by one hand, and its configuration is monitored in real-time by a vision system. By analyzing the acquired images the proper moment for regrasping by the second hand is determined and performed using the existing grasping methods [36].

VII. Human Imitation

In this approach, robotic regrasping is based on imitation from human hand. Through some sensors attached to a human hand, information about relative movements of fingers and their exerted forces are extracted, analyzed, and then replicated on a robotic hand (Fig. 6). Here the regrasping approach employed by the human (e.g. finger gaiting, rolling, sliding) is not important since no planning is done by the robot which acts as a slave agent and just imitates the human. After sufficient training of the robotic hand, it can then perform regrasping operations independently. Only one recent method could be found for this approach.

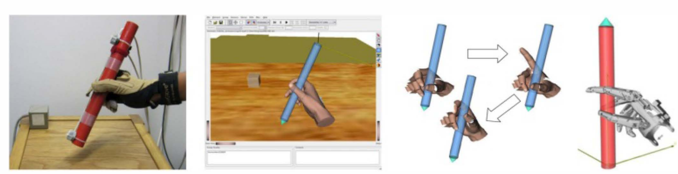

Fig. 6. An example of Human Imitation [37].

A. Tangle Topology

This method uses a technique based on the Tangle Topology in which both the hand and the object are considered as sets of strands (fibers). Then a regrasping movement can be considered as a modification of the Tangle relationship between the hand and the object strands over time. Tangle topology is a geometrical property of the object or hand that describes the relationship of strands: it identifies the twist value between strands and approximate how much they are twisted around each other. For example, we can substitute a hand with ten strands and a cube with twelve strands. In [37] the regrasping movement imitated from human hand are analyzed and reproduced in a robotic hand.

VIII. Throwing and Caching

In this approach, for changing a grasp configuration the object is thrown upwards by the robot's hand and then caught at a new configuration. This concept for regrasping is relatively new and due to its complexity, very few methods have been developed based on it (actually we could find just one!). However, compared to other approaches, regrasping is done much faster by throwing and catching. In this approach, unlike the juggling operation, the final grasp configuration is exactly defined and must be achieved.

A. Vision Feedback

In this method a vision feedback is analyzed in real-time to determine the location and orientation of a simple object. Based on that, the robot's hand changes its configuration in order to throw the object along a specific direction, move toward a new location, and re-catch it by grasping. Fig. 7 shows an example of the method [38].

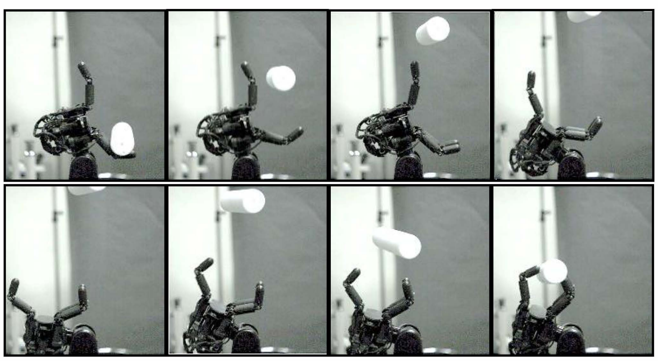

Fig. 7. An example of Throwing and Caching (from top left) [38].

IX. The Taxonomy

The introduced seven fundamental approaches to regrasping were extracted and deduced from a vast body of literature starting from 1987 to 2012. We then tried to categorize relevant researches into these approaches and find a sound relationship and hierarchy between the methods. This hierarchy is depicted in Fig. 8 as a new taxonomy for regrasping. Each method is followed by its corresponding reference number. Most of the methods or approaches had no specific names, and thus we tried to coin proper keywords to describe them as precise as possible. In establishing the approaches and categorizing the methods we tried to keep the amount of mutual overlaps or similarities minimal.

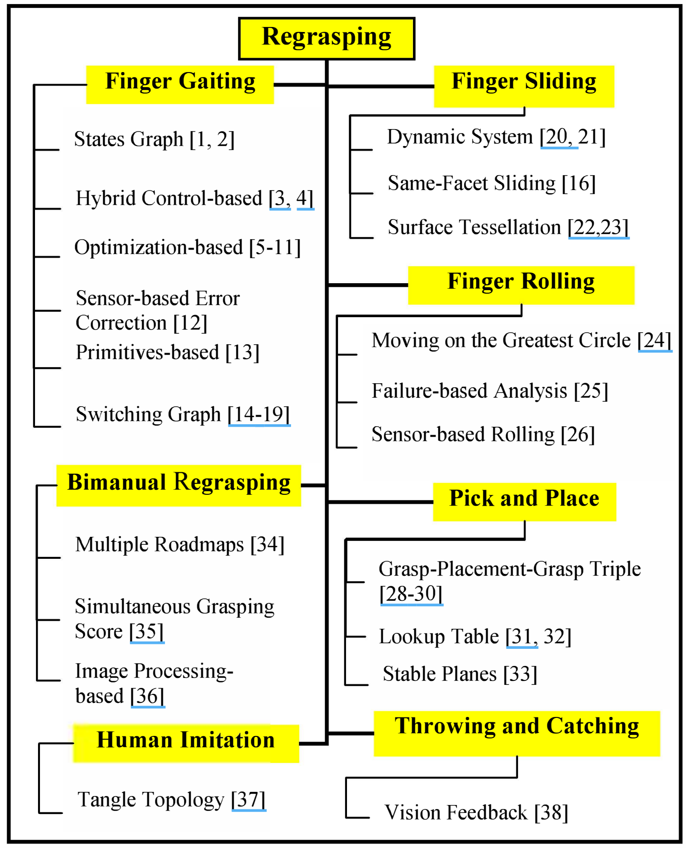

Fig. 8. The proposed taxonomy of regrasp planning.

X. Conclusions

In this paper seven general approaches were introduced as fundamental concepts of regrasp planning. Based on these approaches several methods have been developed throughout the growth of this interesting discipline, of which about twenty important works in the literature have been identified and categorized as a new taxonomy. We have tried to present clear and short descriptions for each approach and method, hoping that it can be useful to researchers in recognizing existing strengths and gaps of the field and conducting their own studies toward new directions. Through our survey it was observed that the Finger Gaiting approach has been considered by much more researchers compared to the Human Imitation and Throwing and Caching approaches, which are in their initial stages of growth. We also could not find applications of intelligent and soft computing methods in the regrasping field.

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