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Slip compensated manipulation of an object with cooperating multiple robots

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SUMMARY

Cooperating multiple robots may experience slips between their end-effectors and the object when making no rigid grasps, as is the case of manipulating fingers. Consequently, these slips make the robotic system unsuccessful in executing a job properly and can even cause a failure of control. Contact-point slips can be avoided by defining multiple constraints on grasping forces and usable workspace, but these constraints limit the utilization of a robotic system. The researchers working on finger grasps and multiple robots cooperation with contact have always been assuming no slips at the contact points. However, in normal practice, one has to encounter this problem. Hence, this paper has taken this contact-point slip problem as its main topic and theme of work. Consequently, the slip phenomenon is analyzed thoroughly and then generalized for a multiple robot system manipulating a geometrically regular-shaped object. Different slip configurations are introduced and methods for their detection are proposed. This detection does not consider dedicated sensors neither for the object's posture nor for the slip detection. It, rather, utilizes only the finger-tip position information usually available from the kinematics based on very common sensors available with the manipulator. Utilizing the proposed methodology, it is possible to detect the end-point slips in most of the cases and realize an exact task execution and stability of control, with a minimum number of sensors.

KEYWORDS: Slip compensation; Cooperating robots; Sensors; Control

1. INTRODUCTION AND BACKGROUND

Cooperation of manipulators increases the dexterity and redundancy of a robotic system. Hence, more difficult tasks can be realized easily with wise planning, along with avoiding different undesirable states and configurations.

The multiple manipulators may either grasp on, or just have point contacts with the object being manipulated. The second concept is well-known for cooperating fingers and dextrous hands. Normally, each finger in a dextrous hand has also a high degree of dexterity but, even then, there are various constraints. Moreover, on the contrary, if a micro manipulation task is considered, it is almost impossible to develop dextrous micro fingers or hands. For such applications, an individual manipulator needs to be very simple in structure and function, or more specifically a uni-functional one.[1]

Salisbury et al. have defined the dynamics of different types of contact-points, and have also introduced the notion of contact centroid for contacts modeled as soft fingers.[2,3] Moreover, different projects have also been undertaken for contact-point localization by force measurements.[4,5] Different types of force closures and form closures are defined which can indicate an optimum number of fingers and their positioning layouts for perfect grasps.[6] Moreover, knowledge for optimum force assignments has been established for stable grasps.[7] On the other hand, Rimon and Burdick have proposed a novel approach to a 2nd order mobility index which defines a minimum number of frictionless contact-points required to immobilize an object.[8] This index requires the contact forces to be always normal to the object's surface to immobilize it against slip. Dextrous fingers can manipulate an object without slips but, on the contrary, it is very difficult to make all the contact forces always normal to the object to achieve this goal with very simple fingers having just one or two degrees of freedom. Such realizations are common on a micro-level, as micro-actuators with multiple degrees of freedom are very difficult to develop and control. Moreover, the above-mentioned goal is even more difficult to achieve if a larger part of the workspace is to be utilized efficiently with slight constraints on manipulation speed and grasping forces. The experimental example considered in this paper will clarify this situation. In conclusion, it can be said that almost all of these research projects are either pre-assuming that no slip occurs during manipulation, or doing something to avoid its occurrence which, consequently, imposes various constraints on the system and makes it even more difficult to realize a job.

"*Slip is not bad if it is known.*" Some people have worked on this approach and utilized the intentional or unintentional slips to solve their problems. Normally, dedicated sensors are used to detect the occurrence of a slip and to measure it. Some common approaches are to use tactile sensors or even visual tracking systems, etc. Multiple publications can be found describing these approaches. It is right to use sensors if the system deserves it, or when it allows the integration of multiple sensors. However, this makes a simple system more complex and even slower while, on the other hand, some systems cannot even allow such provisions.

Considering all these factors and having encountered a real-life problem of such kind, this paper has considered the

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slip problem specifically. Consequently, it proposes a geometrical scheme to detect the occurrence of slip and compensation of its effects using the sensors already available with the system, i.e. no additional sensors are employed. The slip phenomenon is analyzed for its different additional configurations. Most of the results are then generalized for a three dimensional system. As only the geometric parameters are used, which are easily obtained by the available sensors, the computational load is not excessive. Consequently, it has become possible to know about the slip, or even utilize it, without making the system more complex. Although this scheme fails when most of the fingers slip simultaneously, yet it works well for half or lesser number of slipping fingers. An earlier work on this approach working on the planar system only can be found in references 10 and 11.

2. SLIP ANALYSIS

A cooperative manipulation system is composed of at least two manipulators. This is true for large dextrous manipulators. However, the normal convention for dextrous hands is to have at least three fingers. Moreover, in many applications like manipulation of large objects with small mobile robots, this number is needed to be even larger for successful work. For these reasons, this paper also considers at least three cooperating robots to establish the basis of a sensorless slip detection approach.

2.1 Slip Analysis of a Three-Finger System

Consider a three-finger system as shown in Figure 1. If the coordinates of the finger-tips are known in the world frame, a triangle can be formed and lengths of interconnecting lines, or links, can be calculated easily. Now if finger-1 slips, lengths of two links out of three will change. Only this information is sufficient to prompt for the occurrence of a slip. The link changes ΔR_{ij} can be simply known as (i, j being the finger numbers)

$$\begin{aligned} \Delta R_{12} &= R_{1'2} - R_{12} = \Delta R_{21} \\ \Delta R_{13} &= R_{1'3} - R_{13} = \Delta R_{31} \\ \Delta R_{23} &= 0 = \Delta R_{32}. \end{aligned} \tag{1}$$

The sum of absolute changes in the two associated links with a finger, behaving as a vertex, gives a resultant deviation ΔR_i for that finger, and can be expressed as

$$\begin{aligned} \Delta R_1 &= |\Delta R_{12}| + |\Delta R_{13}| \\ \Delta R_2 &= |\Delta R_{21}| + |\Delta R_{23}| = |\Delta R_{21}| \\ \Delta R_3 &= |\Delta R_{31}| + |\Delta R_{32}| = |\Delta R_{31}|. \end{aligned} \tag{2}$$

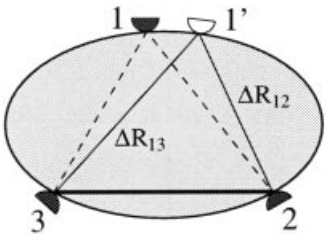


Fig. 1. One-finger slip in a three-finger system.

The above set of equations shows that finger-1 will have obviously the largest value, which will consequently indicate that it has slipped.

On the other hand, if fingers-2 and 3 slip simultaneously without any change in their inter-connecting link R_{23} but finger-1 does not, even then the results obtained will be the same. This is because of the duality that, for a change in two links, only either one finger or the other two should slip simultaneously.

The number of slipped fingers can also be concluded from the number of changed links $N_{\Delta R_{ij}}$. In this case, changes in two links indicate a one-finger slip, while those in three links can happen because of either two-finger or three-finger slips. However, if slipped fingers are restricted to half or less than half of the total number, a correct conclusion can be made.

2.2 Slip Analysis of a Four-Finger System

Any system can show the same results for a one-finger slip as given in the last subsection, but the situation deteriorates when this number increases. Now consider a four-finger system with two slipped ones, as shown in Figure 2. The summation of absolute link changes ΔR_i results in

$$\begin{aligned} \Delta R_1 &= |\Delta R_{12}| + |\Delta R_{13}| + |\Delta R_{14}| \\ \Delta R_2 &= |\Delta R_{21}| + |\Delta R_{23}| + |\Delta R_{24}| \\ \Delta R_3 &= |\Delta R_{31}| + |\Delta R_{32}| \\ \Delta R_4 &= |\Delta R_{41}| + |\Delta R_{42}|. \end{aligned} \tag{3}$$

From this set, it can be judged that either finger-1 or finger-2 slipped. Consequently, the one having a maximum value of ΔR_i will be detected as a slipped finger. The finger with the next highest value can be considered as the second slipped finger if the number of slipped fingers is already correctly known. However, a better way is to exclude the already detected finger and the links associated with it from the system, and re-analyze it as a three-finger system to detect the second slipped finger.

The number of slipped fingers can be found by examining again the number of changed links $N_{\Delta R_{ij}}$. In this system, if one finger slips, exactly three links will change. While if two fingers slip, five links will change, except for some special configurations described in the next subsection. An important point to note is that the fingers can have various

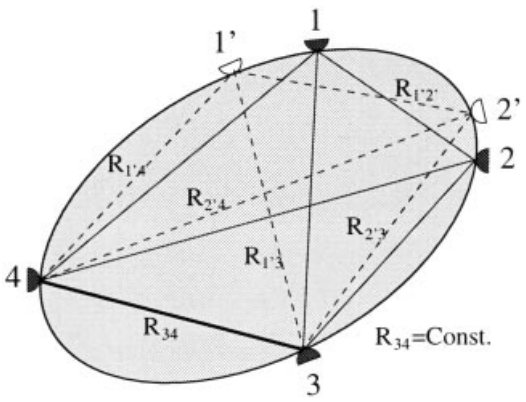


Fig. 2. Two-finger slip in a four-finger system.

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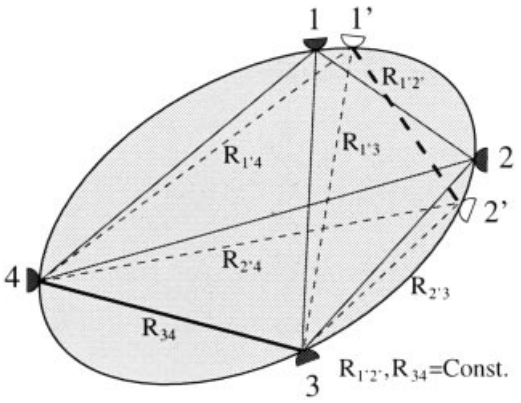


Fig. 3. Dual configuration of a two-finger slip.

different combinations and configurations of slip, and the number of these configurations is normally many times that of the number of slipped fingers.

2.3 Dual Slip Configurations

Consider again the case of a two-finger slip in a four-finger system, but now the link between the two slipped fingers does not change even after the occurrence of a slip. This phenomenon is illustrated in Figure 3. Here again, the resultant absolute deviations of the fingers after slip, ΔR_i, can be written as

$$\begin{aligned}\Delta R_1 &= |\Delta R_{13}| + |\Delta R_{14}| \\ \Delta R_2 &= |\Delta R_{23}| + |\Delta R_{24}| \\ \Delta R_3 &= |\Delta R_{31}| + |\Delta R_{32}| \\ \Delta R_4 &= |\Delta R_{41}| + |\Delta R_{42}|. \end{aligned} \tag{4}$$

In this case, only two changes are associated with all the fingers. Therefore, it is impossible to get any logical indication about the originally slipped fingers. If, for example, a finger is wrongly detected as a slipped one, the method given above for the detection of the second slipped finger will detect another one which will also be wrong. This is because when two fingers slip in a three-finger system with no change in their inter-contact link, then the unslipped one is wrongly detected as a slipped one. As a result, either both the detected fingers will be wrong or both will be correct; there is no possibility of one wrong and one correct detection. That's why such configurations are named as "**dual configurations**." Again there may be many different combinations in this case too.

To detect a dual configuration, fortunately the number of changed links $N_{\Delta R_{ij}}$ helps, which is now exactly one less than that for the simple two-finger slip configurations described above. Special methods are needed to detect the correct fingers, and one possible way is given in this paper.

3. A MULTIPLE ROBOT SYSTEM WITH FRICTIONAL POINT CONTACTS

This section generalizes the slip analysis for a multi-fingered system.

3.1 Important Considerations

Before proceeding with this, some important assumptions are furnished as follows:

- Only the systems with three or more fingers are considered.
- The conclusions and all the rules are generally applied to a somewhat geometrically regular-shaped object. Particularly, the object should not be very irregular having sharp peaks and valleys on its surface.
- When a finger slips, all the links associated with it must change. However, the links between two slipped fingers can retain their lengths. This also relates to the shape of the object being handled which can allow some links to retain their lengths even after their joining fingers have actually slipped.
- The length of a link should never approach a zero value.
- Only half or fewer fingers can slip simultaneously, or specifically, at least two fingers must remain unslipped even for a three-finger system during a sampling interval.

3.2 Foundations for Slip Detection

Consider an object being manipulated by "*n*" robots, or fingers, as shown in Figure 4.[9] Since only the finger-tips of the manipulators in-contact with the object are important, hence the following conclusions are true for any type of manipulator. The end-point coordinates of a manipulator $({}^o x_i, {}^o y_i, {}^o z_i)$ can be obtained very easily with respect to a universal frame Σ_o, using the kinematic relationships of this manipulator.

Consider "*m*," or at least one, fixed points on the surface of the object in the plane of motion. These points are regarded as "**landmarks**" and help to re-allocate the slipped fingers when no other information is available. The positions of landmarks are known initially with respect to each finger-tip, and can easily be calculated using the current object's posture and/or the unslipped fingers.

If all the finger-tips and the landmarks are interconnected, a mesh of "**links**" is formed. The intercontact-point link lengths can be simply known as

$$R_{ij} = \sqrt{({}^o x_i - {}^o x_j)^2 + ({}^o y_i - {}^o y_j)^2 + ({}^o z_i - {}^o z_j)^2} \tag{5}$$

where $i, j = 1,2, \ldots, n$ but $i \neq j$. The maximum number of inter-contact links $N_{R_{ij}}$ can be found by solving the arithmetic series ${}^nC_2$ as

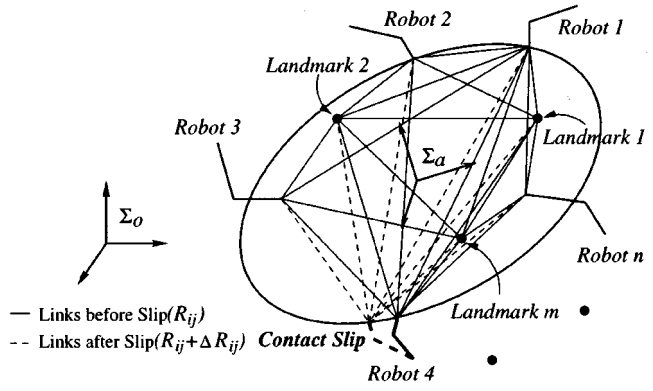


Fig. 4. Illustration of slip phenomenon.

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$$N_{R_{ij}} = \frac{n(n-1)}{2}. \quad (6)$$

Similarly, number of inter-landmark links $N_{R_{kl}}$ can be found by solving the arithmetic series ${}^{m}C_2$, and that for contact-point to landmark links is simply

$$N_{R_{ik}} = m \times n. \quad (7)$$

Now if "n_s" fingers slip, the number of different slip configurations is usually

$$N_{slip} \geq n_s^2. \quad (8)$$

As a finger slips, the changes in inter-contact links can be calculated as

$$\Delta R_{ij} = R_{ij}(t) - R_{ij}(t-1) \quad (9)$$

where $R_{ij}(t)$ is the link length in t^{th} sampling interval, while $R_{ij}(t-1)$ is one in the last interval.

For different slip configurations of a particular number of fingers, the number of changed inter-contact links $N_{\Delta R_{ij}}$ is also different. An upper limit exists when all the links with slipped fingers change, and is calculated by summing up the arithmetic series from $(n-1)$ to $(n-n_s)$, which results in

$$N_{\Delta R_{ij},max} = \frac{n_s\{2n-(n_s+1)\}}{2}, \quad (10)$$

while a lower bound is found by subtracting the number of links between slipped fingers, ${}^{n_s}C_2$, when they remain unchanged even after a slip has occurred.

$$N_{\Delta R_{ij},min} = n_s(n-n_s). \quad (11)$$

It is notable that the upper bound is valid for simple slip configurations while the lower one is true for almost all dual configurations.

3.3 An Important Observation

Considering the above rules, it can be observed that for a regular-shaped object,

- when the number of changed links is $N_{\Delta R_{ij}} < n-1$, i.e. one less than the total number of fingers, then "**no slip**" has occurred, and
- when $N_{\Delta R_{ij}} \geq n-1$, then "**a slip**" has definitely occurred.

4. SLIP DETECTION AND COMPENSATION ALGORITHM

Now it is time to develop a tool for detection and compensation of slip using the information furnished in the above sections.

As it is known that, for a particular number of slipped fingers there exists a range of changed intercontact links from $N_{\Delta R_{ij},min}$ to $N_{\Delta R_{ij},max}$; this means that the same value of $N_{\Delta R_{ij}}$ can exist for different number of slipped fingers depending on whether a slip configuration is a simple or dual one. It is true as these ranges are not necessarily apart. Therefore, an obtained number for $N_{\Delta R_{ij}}$ does not necessarily correspond to only one slip configuration and, for that reason, all such configurations are to be checked one by one.

4.1 Recursive Detection of Slipped Fingers

This subsection gives an estimate of the number of slipped fingers, and the actual fingers which have slipped. It considers all possible values of n_s corresponding to an achieved value of $N_{\Delta R_{ij}}$. The important steps of the procedure are as given below:

(i) Select the least possible value of n_s.
(ii) Calculate ΔR_{ij} using equation (9).
(iii) Note if it is a dual configuration.
(iv) For each finger, calculate the following **"slip indication factor"**

$$S_i = \sum_{j=1}^{n} |\Delta R_{ij}| \quad (12)$$

where $i = 1, 2, \ldots, n$ and $i \neq j$.

(v) Take the finger with the maximum value of S_i as a definitely "slipped" one.
(vi) Exclude the slipped finger and all the links associated with it from the next steps of algorithm.
(vii) Reduce n_s by 1, and repeat steps (iv)–(vi) for remaining slipped fingers until $n_s = 0$.
(viii) Store all the new found information about slipped and unslipped fingers.
(ix) Repeat steps (ii)–(viii) for a next probable higher value of n_s.

4.2 Decision and Slip Determination

To decide about a correct set of slipped and unslipped fingers, the links between any two unslipped fingers are taken as reference. In the worst case, at least one finger must be unslipped, then the landmarks are used to provide some reference geometrical information in combination with this only unslipped finger. The algorithm proceeds further as follows:

(x) Calculate all finger slips geometrically using reference information for each set obtained above.
(xi) Calculate a new object posture.
(xii) Compare this new posture with the probable one as interpolated between the reference inputs and the one in the last sampling period. Another way is to extrapolate only the previous postures to know the probable new one.
(xiii) The set with minimum errors is taken as the correct solution.

In the algorithm, all steps applicable to landmarks are also executed.

4.3 Detection for a Dual Configuration

If a dual configuration is detected at step (iii) above, all the results need to be checked again. It is known that in such configurations, either all the detected fingers have actually slipped or none of them has slipped. This information is utilized to check them by the following geometrical method.

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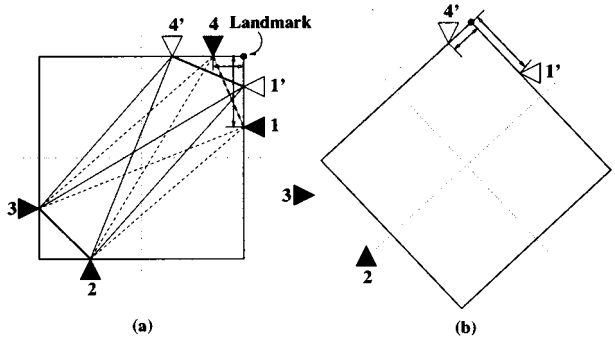


Fig. 5. Detection for dual configuration slip.

This check will be clarified by a practical example shown in Figure 5a. Fingers 1 and 4 slip simultaneously with no change in the link R_{14}, i.e. $\Delta R_{14} = 0$. As the number of changed links $N_{\Delta R_{ij}} = N_{\Delta R_{ij},min} = 4$, a dual configuration is indicated. If vertices of the object are taken as landmarks, the distances of finger-tips from them are known in a servo control interval. Now, if fingers 2 and 3 are wrongly detected to be slipped ones, in this case, fingers 1 and 4 should have the same distances from the landmarks as before. This will result in a new object posture shown in Fig. 5b, and will indicate that both fingers 2 and 3 are no more on the surface of the object. Hence, another trail with fingers 1 and 2 will result in a correct detection. Unfortunately, this check cannot work for precisely circular or spherical objects as re-orientation produces no change.

5. SIMULATIONS AND OBJECT MANIPULATION EXPERIMENTS

Though the formulations given in the above sections are for a general three dimensional multiple manipulator system manipulating an object in space, yet the simulations and experiments are performed for a planar system only. The reason is that this research work has been undertaken for this particular system at the start and then only the theories are extended and generalized for a three dimensional system. However, as all the parameters considered are only scalars, hence no real conflict or mishap can be expected. The occurrence of a slip has been very evident in the planar system under consideration.

5.1 The Experimental System

Figure 6 shows the experimental cooperative manipulation system TEBOT (TE roBOT; "TE" means a "hand" in Japanese). It has generally four or more individual robots, i.e. fingers. Each finger has only one active degree of freedom which is the motion of the push rod, while it can rotate passively through almost 30° on either side of its equilibrium position. This passive motion is constrained by a spring-damper assembly.[9] In such systems, occurrence of a contact-point slip is very evident as the system is an under-actuated one and has only point contacts with the object.

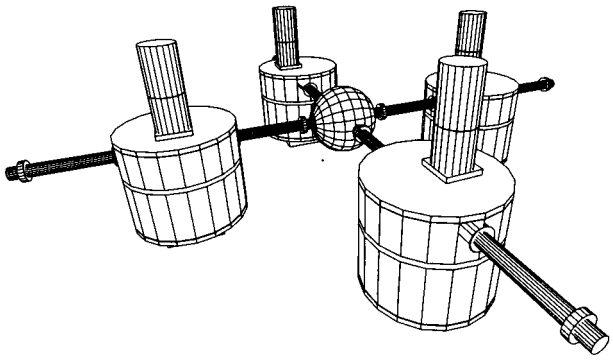


Fig. 6. Overview of the experimental system.

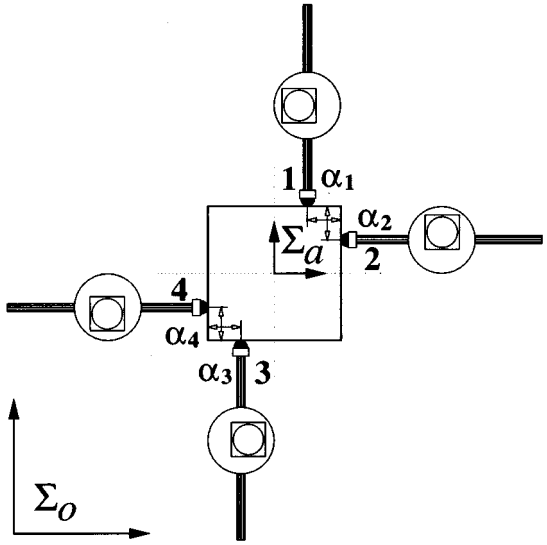


Fig. 7. System configuration used in experiments.

The configuration used in the simulations and experiments, to verify the slip detection methods developed, is shown in Figure 7. This type of grasping configuration has been found very efficient for a perfect force closure definition on the object for its immobility, and for all possible manipulations in a plane.[6,8]

5.2 Modified Control Algorithm

To control a multiple manipulator system of such kind, a hybrid position and force control algorithm is used. From posture error, the resultant external forces on the object are calculated and then the force is distributed over all the robots to manipulate the object to the desired posture. Both internal and external forces are to be controlled, so that the object may be safely manipulated without either dropping due to weak forces or deforming due to unnecessarily large force. In the feedback, only the joint information of the robot is acquired which is then used to calculate the current real posture of the object using simple kinematic rules.

At this stage, if a slip has occurred during current manipulation, a wrong current posture will be known which will definitely give erroneous information to the controller. Therefore, as soon as the sensors' data is acquired, it needs to be analyzed for any occurrence of a slip. If a slip is detected, the amount of the slip is to be determined and the current posture of the object is to be modified to be as close to the real as possible. This process is illustrated in Figure 8.

If at the slip detection block, no slip is detected, the data simply passes to the current posture calculation block. However, in case of a slip all the slip determination and compensation algorithm given in this paper are executed.

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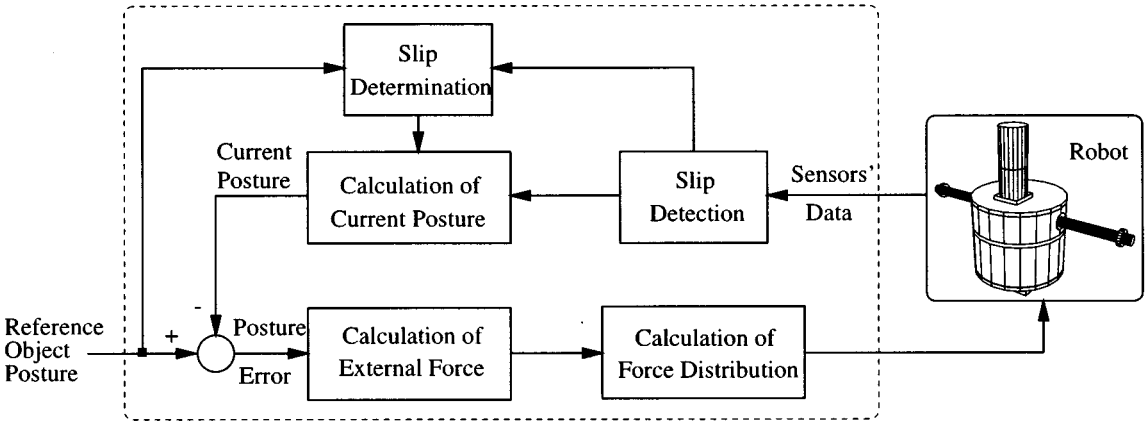


Fig. 8. Modified control system with slip detection/compensation.

Finally, the newly known posture is directly compared with the reference input to decide whether the determination of slipped fingers and compensation are correct or not. Moreover, in case of a dual configuration the geometrical algorithm for its determination is also executed at this stage. In the worst case, if it is impossible to determine the actually slipped fingers and compensate the amount of slip or most of the fingers are affected by a slip, the control algorithm stops the task execution.

5.3 Simulations

The slip detection scheme is mathematically simulated for the system of Figure 7, for various different slip configurations to check its validity and applicability. Table I shows the detection results for both the cases when no check for dual configurations is applied, and when the geometrical method given in section 4.3 is used (status with "*"). A correct detection is marked with a "C" while a wrong one is marked with a "W". It is clear that all simple slip configurations for one finger, two fingers and even three fingers are correctly detected, while most of the dual configurations cause generally wrong detections. However, the same dual configurations are also detected correctly when a dual configuration check, introduced in this paper, is applied.

5.4 Experiments and Discussion on Results

Figures 9 through 12 show the results of object manipulation with the TEBOT system under consideration. The figures plot the position (x, y) of the object in the plane, its orientation θ, and distances of the finger-tips from landmarks, taken as the initially nearest vertices of the object, α_i, as described in Figure 7.

Figure 9 shows the results when object is manipulated without slip detection/compensation. As a finger slips, the system tries to control the object and that's why there are large variations in both position and orientation. But ultimately the oscillations start diverging, as the other fingers also leave their spots, causing the object to drop at the end of trajectory execution. In even more severe case, the object may drop immediately. Figure 10 shows the results of object manipulation in the $x-y$ plane without any change in its orientation. Only a one-finger slip occurs at a moment which causes a change in the object posture. However, it is immediately detected and compensated before the system goes unstable. Figure 11 also shows almost the same results but now for the object manipulation consisting of both translation and rotation. Here also, a one-

Table I. Simulation results without and with dual configurations' check.

Finger status				Results obtained	
1	2	3	4	Slipped fingers	Status
One-finger slip					
S	NS	NS	NS	1	C/C*
NS	S	NS	NS	2	C/C*
NS	NS	S	NS	3	C/C*
NS	NS	NS	S	4	C/C*
Two-finger simple slip					
S	S	NS	NS	1 & 2	C/C*
NS	S	S	NS	2 & 3	C/C*
NS	NS	S	S	3 & 4	C/C*
S	NS	NS	S	1 & 4	C/C*
Two closer fingers (dual slip)					
S	NS	NS	S	1 & 4	C/C*
Two longer distance fingers (dual slip)					
S	S	NS	NS	3 & 4	W/C*
Two diagonally opposite fingers (simple slip)					
S	NS	S	NS	1 & 3	C/C*
Two diagonally opposite fingers (dual slip)					
S	NS	S	NS	2 & 4	W/C*
Three-finger random slip					
S	S	S	NS	1, 2 & 3	C/C*
S	NS	S	S	1, 3 & 4	C/C*
NS	S	S	S	2, 3 & 4	C/C*

S = Slipped, NS = Not Slipped
C = Correct, W = Wrong
* = Results with dual configurations' check

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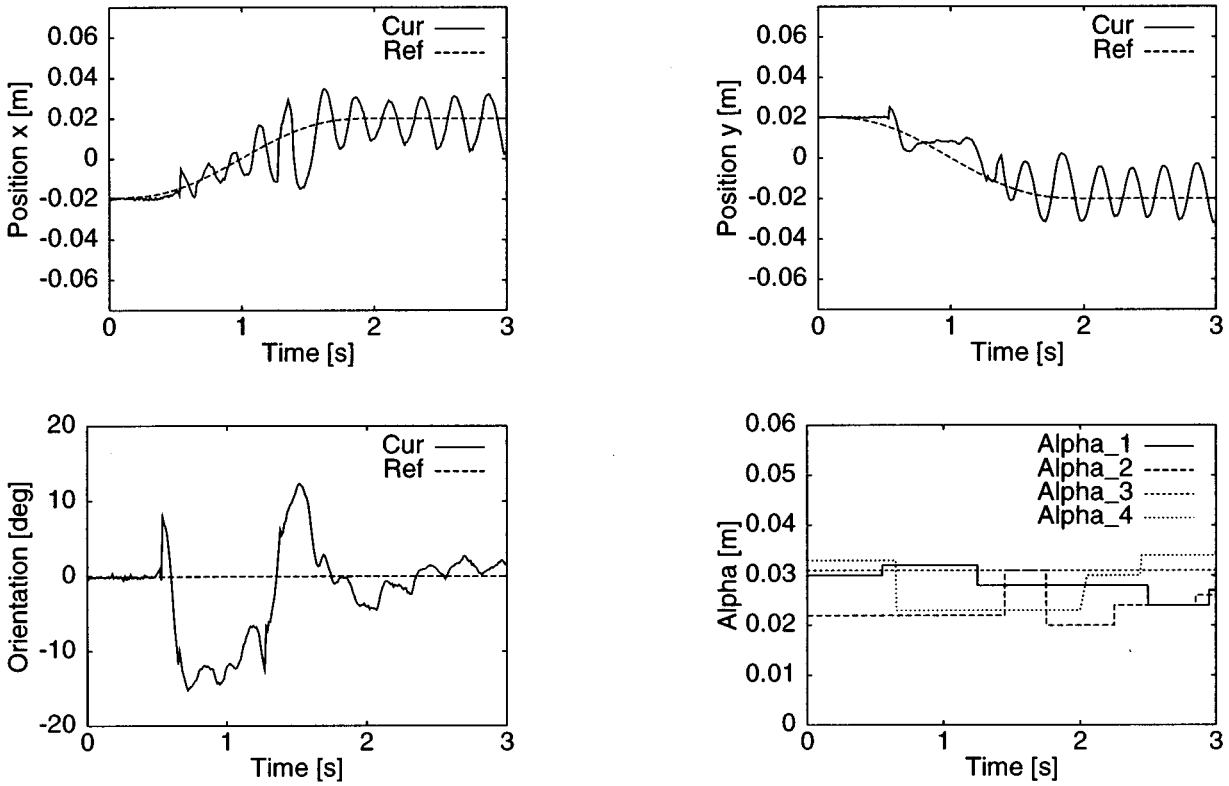


Fig. 9. Experimental results without slip detection (with slip).

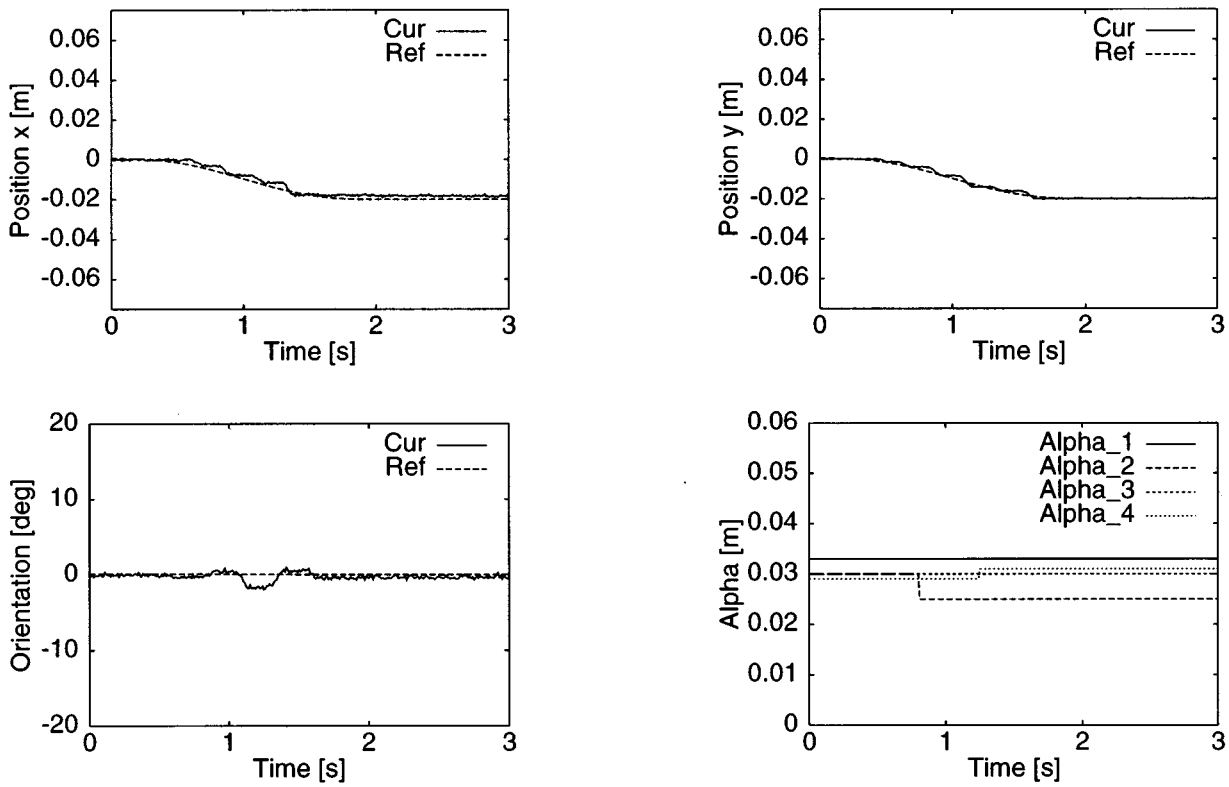


Fig. 10. Object translation with one-finger slip detection.

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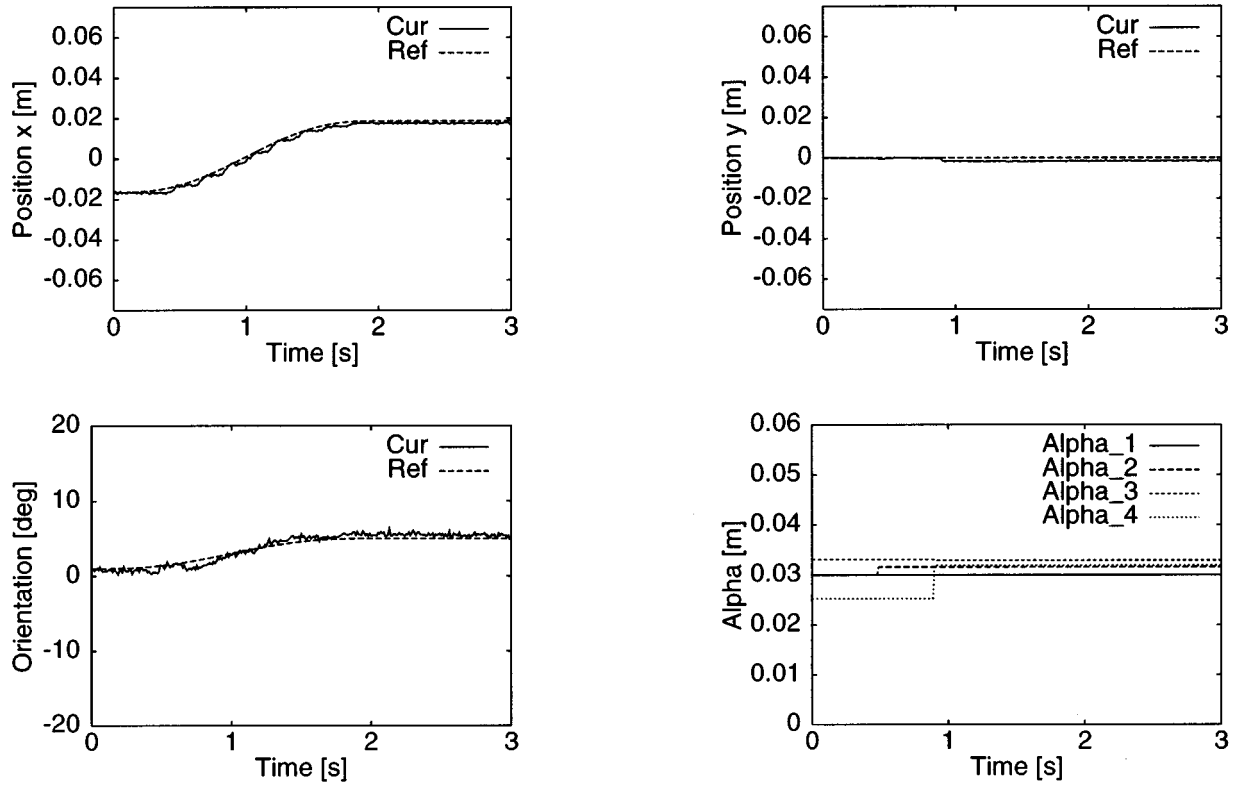


Fig. 11. Object translation and rotation with one-finger slip detection.

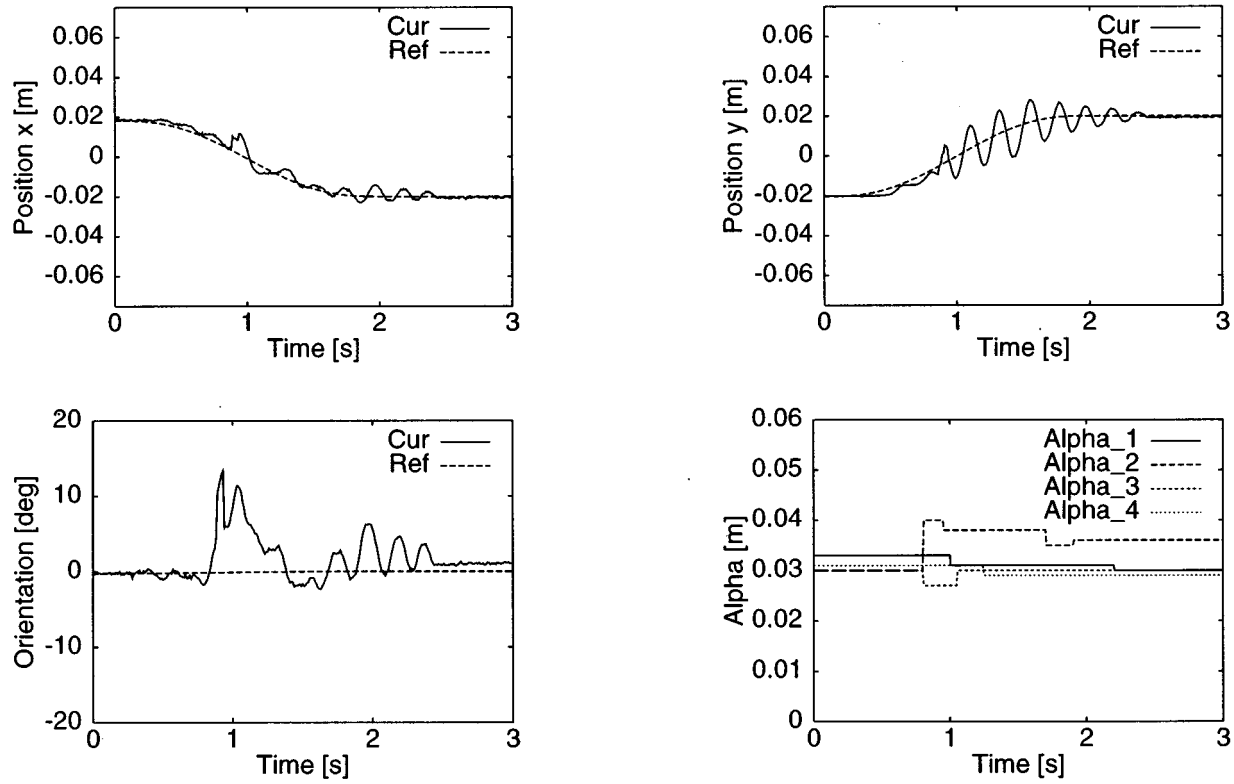


Fig. 12. Object translation with two-finger slip detection.

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finger slip could be detected at an instance and hence compensated immediately, thus resulting in a stable task execution. Figure 12 shows the manipulation results when two fingers observe large slips simultaneously within a single sampling interval during translation of the object, thus causing a greater disturbance to the system. Though the system gets closer to the verge of instability and large variations in both position and orientation are observed, causing many other slips, yet the slip algorithm has been able to detect and precisely compensate the occurred slips leaving a stable posture with a very small offset.

It can be observed that there remain small steady state errors in both position and orientation of the object in almost all cases. These errors are mainly due to the improper modeling and control parameters of the experimental system and do not indicate any problems with the proposed slip detection/compensation method. Actually, a robot in this system exhibits a large friction in its push rod which is difficult to overcome when the trajectory error is quite small. Moreover, it is also normally difficult for the system to compensate an orientation error when it is not being commanded for the object orientation change. Moreover, the oscillations in Figure 12 are due to large simultaneous slips and greater deviations in orientation. Therefore, when the slips are compensated, the oscillations die down automatically and the orientation error is also reduced to almost the same value as before.

From the above simulations and experimental implementations, it can be concluded that the proposed sensorless slip detection and compensation scheme can successfully do its job for any general multiple manipulator system manipulating an object with only point contacts. With application of this scheme, the experimental system under consideration has been able to maintain the control and compensate for the effects of occurred slips.

6. CONCLUSIONS

In this paper, the contact-point slip problem for cooperating multiple manipulators/fingers has been introduced. The slip phenomenon is analyzed and different detectable and undetectable configurations are distinguished. The generalized results are formulated in the form of a recursive algorithm for the detection and important steps for compensation of the finger slips. This is done for a system having a minimal number of sensors and even with no dedicated sensors employed for the posture of the object being manipulated and for slip detection. The proposed method works well for a mostly geometrically regular-shaped object with a particular number of slipped fingers, which is half or generally fewer than the total number of fingers. Different mathematical simulations are performed to find the efficiency of detection and then experiments are done with a special multiple manipulator system which can easily exhibit the slip phenomenon. Experimental results have shown the applicability of the proposed scheme. It is hoped that, with a few modifications, the method will be able to work for an irregular object too. However, the effectiveness of the proposed scheme depends on most of the assumptions made in this paper.

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