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INVESTIGATION OF MASS CENTER UNCERTAINTY FOR SAFE GRASPING BY A TWO FINGER HAND

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Abstract – Grasping and handling delicate objects with robotic systems need a sophisticated control capable of grasping the object with minimum possible normal force. To devise and implement such a control, one needs to employ a complete dynamic model which accounts for multi phase columb friction. It is a common practice among researchers to simplify the real multi phase friction with a single one such as slipping mode. This paper employs a controller which is based on measurement of the contact and friction forces, instead of measuring relative velocity and acceleration between object and gripper. This controller takes advantage of an estimator for friction coefficient. Main objective of this paper is to present a mathematical model for dynamics of a grasped object which accounts for effects of uncertainty in mass distribution. The model, then, is employed to investigate effect of mass centre uncertainty in estimation of friction coefficient and performance of controller.

Index Terms - safe grasping, multi-phase friction, columb friction, mass distribution uncertainty

1 Introduction

As the robotic systems improve and become more autonomous, grasping becomes more important and more attention is paid to that by researchers. Holding and manipulating delicate objects such as a glass of water, introduces the concept of safe grasping. When a robot manipulates a delicate object, it must grasp it in a stable way to prevent slipping by applying the minimum necessary grasping force to avoid object breaking or deformation.

Safe grasping can be accomplished by two different ways, the first – called form closure – is based on handling object with frictionless contacts, while, the second – called force closure – is based on holding the object by applying proper amount of friction force to it. Although, the first method of grasping seems to be more convenient for safe grasping purpose, but it needs very good knowledge of the geometry of the object, besides it needs a dexterous hand which has enough fingers to hold the object in a stable way. Due to uncertainty in object shape, form closure is not a suitable method for grasping unknown objects or objects in unknown circumstances. On the other hand, force closure, which could be regarded as the solution for grasping of unknown objects, needs good detection of object slipping and use of this information in control of the fingers in order to hold the object with minimum necessary force - like the human hand does.

Last decade, considerable research work has been done in the area of object manipulation using tactile sensors. Two classes of problems seem to predominate in this area of research: (i) detection of object slippage (ii) real time force control of gripper.

Some researcher worked on designing different type of tactile sensors [1-5]. They present appropriate models for slippage detection based on frequency response of measured contact forces. As opposed to the issue of slippage detection, the subject of force control for safe grasping shows less progress. [6-12] show some typical references on this subject. Most of controllers used to achieve stable grasp need good knowledge of relative motion, i.e. relative velocity and relative acceleration between gripper and the object. Non-zero relative velocity means that the object is slipping; whereas, non-zero relative acceleration with zero relative velocity shows that the object is about to slip which means that the system is in incipient slip mode.

This type of controllers face two kinds of difficulties the first is due to errors resulted from numerical derivatives needed for calculation of relative motion. The second difficulty arises from the fact that this type of controllers has no sense of excessive normal forces which might be exerted on the object by gripper, so it is not capable of reducing the normal force to its minimum necessary value. In contrast to this, some researches reported that controllers which are merely based on relative motion information are capable of reducing excessive normal force. As an example we may consider the results reported by Glossas and Aspragathos[5]. Ahmadi and Sadigh [13] revealed that such good results could not be obtained in real situation. They showed that the reported good results are obtained by employing an erroneous simplified linear model for Coulomb friction. They further developed the work and proposed a control scheme based on sensing normal and friction force [14], instead of relative motion. They also presented an estimation algorithm for friction coefficient.

Grasping unknown objects, the system must be robust against different uncertainties, which must be further investigated. Uncertainties in mass and mass distribution are two important uncertainties which might be encountered during grasping of unknown object. The robustness of controller proposed in [14] in presence of mass uncertainties was investigated in that paper. However, the effect of uncertainties in mass distribution was not considered. Mass distribution uncertainty is a difficult phenomenon to investigate. For, uncertainty in mass center may cause the object to rotate with respect to gripper, so the mathematical model must account for different possible contact points and a distribution of contact and friction forces. Also, the model must account for different possible phases of rotational and linear slippage. To this end, a mathematical model is developed which assumes that contact forces are applied along a contact line between gripper and object, see Figure 1. The model accounts for different phases of relative motion between object and gripper; i.e. non-slip, rotational slip, translational slip, rotational incipient slip and linear incipient slip modes, Figures 2 and 3.

2 Mathematical modelling

As stated in previous section to be able to investigate the effect of mass distribution uncertainty, one needs first to develop a mathematical model which accounts for different possible modes of relative motion between gripper and object. In this section we first derive equations of motion for the grasped object and then complete the model by developing mathematical model for coulomb friction forces in different modes of relative motion.

2.1 Dynamic equations of motion

The system under consideration is a prism grasped by a two-finger gripper of a robotic manipulator. The manipulator is assumed to move the object in vertical plane. The gripper jaws are two plates covered with elastic material to provide both good compliance and good friction coefficient. To model dynamics of the system following assumptions are made:

1- The object is symmetric related to y-z plane.

2- The normal force are uniformly exerted on the grasped object along a line on which force sensors are arranged, see Figure 1.

3- Motion takes place in y-z plan along y direction.

4- Masscenter has an offset c with respect to the center of sensor line, o, see Figure 2.

5- Stiffness coefficients on both gripper jaws are equal.

6- Rotations due to slip of object is small, so no part of force sensor line loses contact with the object and position of center of mass does not change along z direction.

Above assumptions mean that:

1- Due to symmetric of the system, normal and friction force distribution in both gripper faces are the same.

2- In spite of uniform normal force distribution, friction force has non uniform distribution in z direction, which is a consequence of mass uncertainty or unbalanced mass distribution in y-z plane.

Free body diagram of the system is shown in Figures 1 and 2 To write equations of motion of the object let us replace the distributed normal forces with its equivalent which passes through o, the midpoint of sensor line. We also replace friction forces with its equivalent set of resultant force, F_y passing through center of mass and a couple τ_f. Equations of motion of the object can be written as:

$$2F_y - mg = m\ddot{y} \tag{1}$$

$$2\tau_f = I_{xx}\ddot{\theta}_x \tag{2}$$

in which the terms m, I_{xx} and $\ddot{\theta}_x$ are, respectively, mass, central moment of inertia and the magnitude of angular acceleration of the object. Equations (1) and (2) are equations of motion of the object; however, to have a complete dynamic model one needs to relate friction forces; i.e. F_y and τ_f to the normal force, N. To this end, one needs to consider different possible modes of motion between object and gripper, and to establish a distribution force pattern for each mode.

2.2 Friction force pattern in different modes

As mentioned in previous section, considering the symmetry about y-z plane, there would be five different modes of relative motion between gripper and the object. To have a better understanding of what these modes are and what is the friction force pattern in each mode; let us assume that the normal force exerted on an object which is hold by a gripper is increased step by step. So, that the object experiences different modes of motion. Figure 3-a shows the friction force pattern when the normal force N is so small that the object is slipping down.

In this situation the intensity of friction force, f along the sensor line is constant and equals to μn, where μ is friction coefficient and n is the intensity of normal force defined by

$$N = nb \tag{3}$$

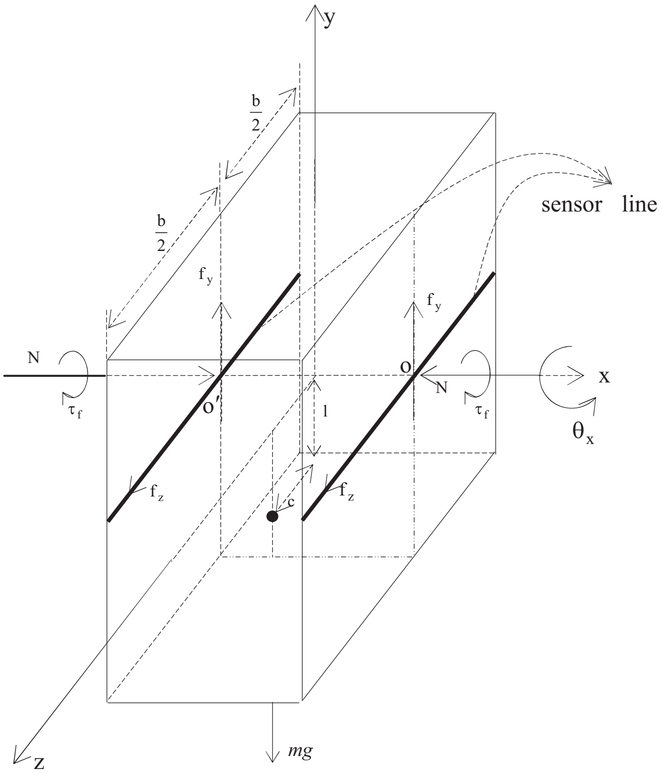


Figure 1 free-body diagram of grasped object

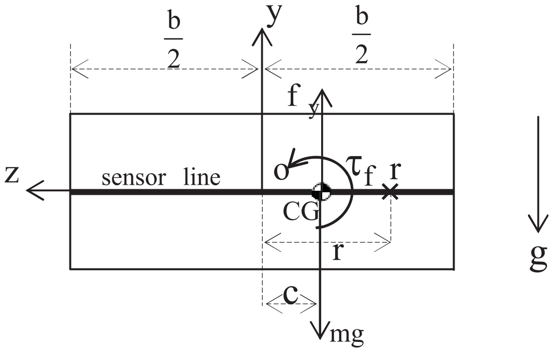


Figure 2 forces applying on object as seen from right side

where b depicts gripper jaw width. Increasing the normal force causes f to increase until friction forces on two sides just balance the weight. At this time the system is at incipient linear slip mode. In this case the friction force pattern is still the same as Figure 3-a. This pattern of friction force in presence of mass centre uncertainty; i.e. c not equal zero, produces a torque which rotates the object. Further increase of normal force, considering that the integral of friction forces should remain constant and equal to object weight, moves point r, centre of angular velocity, toward o. In this situation the friction force pattern is similar to what is shown in Figure 3-b. This continues until friction torque, τ_f, vanishes, i.e. the torque of upward friction forces about mass centre just balances the torque of downward friction forces. In this situation the object is at the verge of rotation so it is in rotational incipient mode, and still has the same force pattern as fig 3-b. As the normal force continues to increase, the object stops slipping and the friction force pattern becomes of the form 3-c. Further increase of normal force increase f_s and causes the friction force to find a pattern similar to Figure 3-d. Increasing N from the point does not change the mode of relative motion; however it changes the pattern of friction forces to what is shown in Figures 3-e and 3-f.

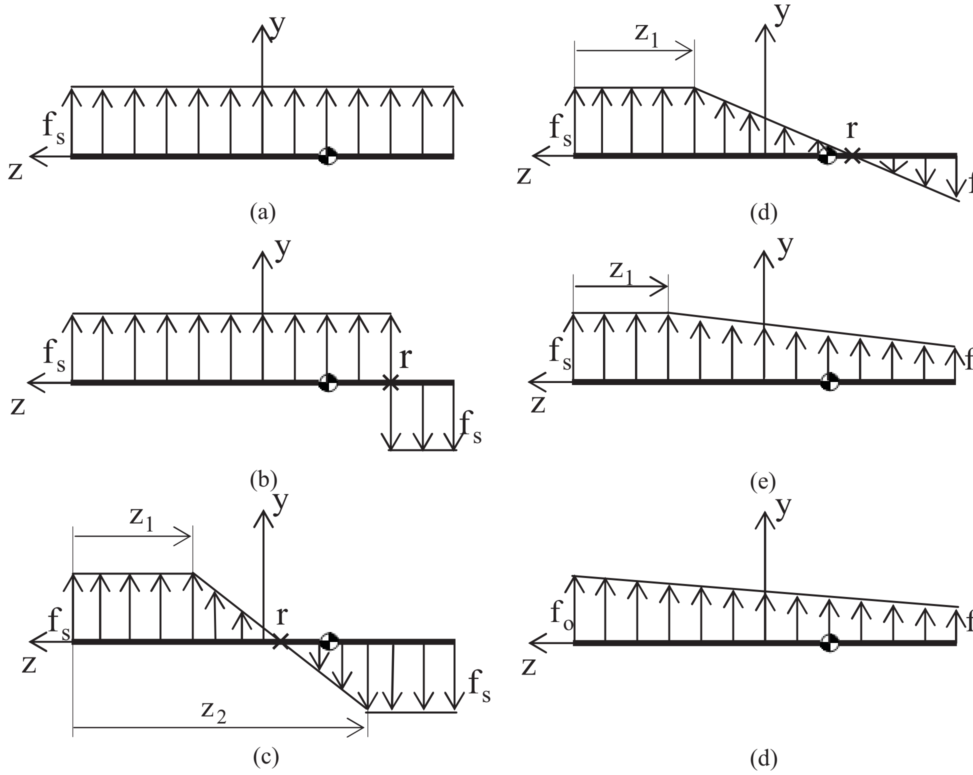
2.3 Equations of motion in different modes

Considering that gripper is moving with of $\dot{y}_d$ and acceleration of $\ddot{y}_d$, we may write equations of motion in different modes as follow:

Translational slipping mode. In this mode all points on contact line has a relative velocity different from zero or in other words relative velocity along contact line has similar sign. In this case we can write

$$F_y = -\mu N \operatorname{sgn}(\dot{y} - \dot{y}_d) \tag{4}$$

$$\tau_f = -\mu N c \tag{5}$$



(a) (d) (b) (e) (c) (d)

Figure 3 pattern of friction forces in different modes of motion

substituting these in equations (1) and (2) gives

$$-2\mu N \operatorname{sgn}(\dot{y} - \dot{y}_d) - mg = m\ddot{y} \tag{6}$$

$$I_{xx}\ddot{\theta}_x = -2\mu N c \tag{7}$$

Rotational slip mode. In this mode relative velocity along contact line differs from zero on every point except point r; see Figure 2 and 3-b. Considering the pattern of friction forces, we obtain the following relation for F_y and τ_f:

$$F_y = -2\mu N r / b \operatorname{sgn}(r\dot{\theta}) \tag{8}$$

$$\tau_f = -\mu N(r^2 + 2rc - b^2/4)/b \tag{9}$$

Substituting these relation into equations (1) and (2) yields

$$m\ddot{y} = -4\mu N r / b \operatorname{sgn}(r\dot{\theta}) - mg \tag{10}$$

$$I_{xx}\ddot{\theta}_x = -2\mu N(r^2 + 2rc - b^2/4) \tag{11}$$

Incipient translational slip mode. As the pattern of forces in this case is similar to translational slipping mode equations of motion are exactly the same as translational slipping mode.

Incipient rotational slip mode. With the same reason as explained above the equation of motion for this mode is also similar to rotational slipping mode.

Non slip mode. In this mode the relative motion between gripper and object is equal to zero so we may write

$$\ddot{y} = \ddot{y}_d \tag{12}$$

$$\ddot{\theta}_x = \ddot{\theta}_d = 0 \tag{13}$$

substituting these relations in equations of motion one gets

$$F_y = m\ddot{y}_d \tag{14}$$

$$\tau_f = 0 \tag{15}$$

This means that the friction force pattern is adjusted so that the resultant of the friction forces passes through mass center and equals the weight minus inertia forces of the object.

3 Forces-Based control

As stated before, authors of this paper previously proposed a controller which does not need any information of relative motion [14]. Instead, it uses the normal and tangential force as feedback and based on it decides whether to close the gripper or not. The proposed control has the following form for the closing speed of fingers of the gripper:

$$\dot{x} = (\nu - k_N(N - k_\mu f/\mu)) \tag{16}$$

In which k_N, k_μ and ν are some constants. N, μ, and f are, respectively, the normal force, coefficient of friction between gripper and object, and friction force- here F_y. The first term in this controller gives a constant intention of closing the gripper with a speed of ν; while the second term gives an intention of opening the gripper with a speed proportional to $k_N(N - k_\mu f/\mu)$ which is an indication of excessive applied normal force. The action of this control is such that at the beginning of grasping procedure, when normal and friction forces are zero, it closes the fingers with the speed of ν. As the normal force increases and exceeds the necessary amount of normal force the second term starts to reduce the closing speed and even may reverse the direction of $\dot{x}$ and opens the gripper. This procedure ends when these two intentions get balanced.

4 Numerical results

Using the dynamic model developed in section 3 the motion of gripper controlled by a controller introduced in section 3 is studied. Physical properties of the system and constants of controller are as follows: m=1 kg, $I_{xx} = 0.006$ kgm^2, c=0.001 m, b=0.2m, $\mu = 0.4$, $k = 10000\,N/m$, $k_N = -0.75$, $k_\mu = 1$, and $\nu = 0.225$. The system is studied in two cases, in the first case gripper is stationary and it only tries to hold the object; whereas, in the second case gripper has to move the object with desired velocity as given in Figure 4. The results for first case are shown in Figure 5 where the results for the second case are shown in Figure 6. As the results show the controller can hold the object with minimum necessary normal force. However, it is also evident, as expected, with this minimum normal force the object rotates due to mass distribution uncertainty. This problem can be treated either by applying larger normal force, which is inconvenient, or by using a third finger to apply a force in z direction to prevent rotation. Also this problem can be treated by using a hand with multi segment fingers to make it possible to apply different normal force and produce necessary friction moment to prevent rotation.

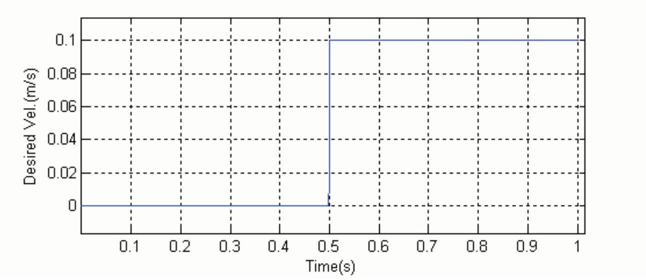
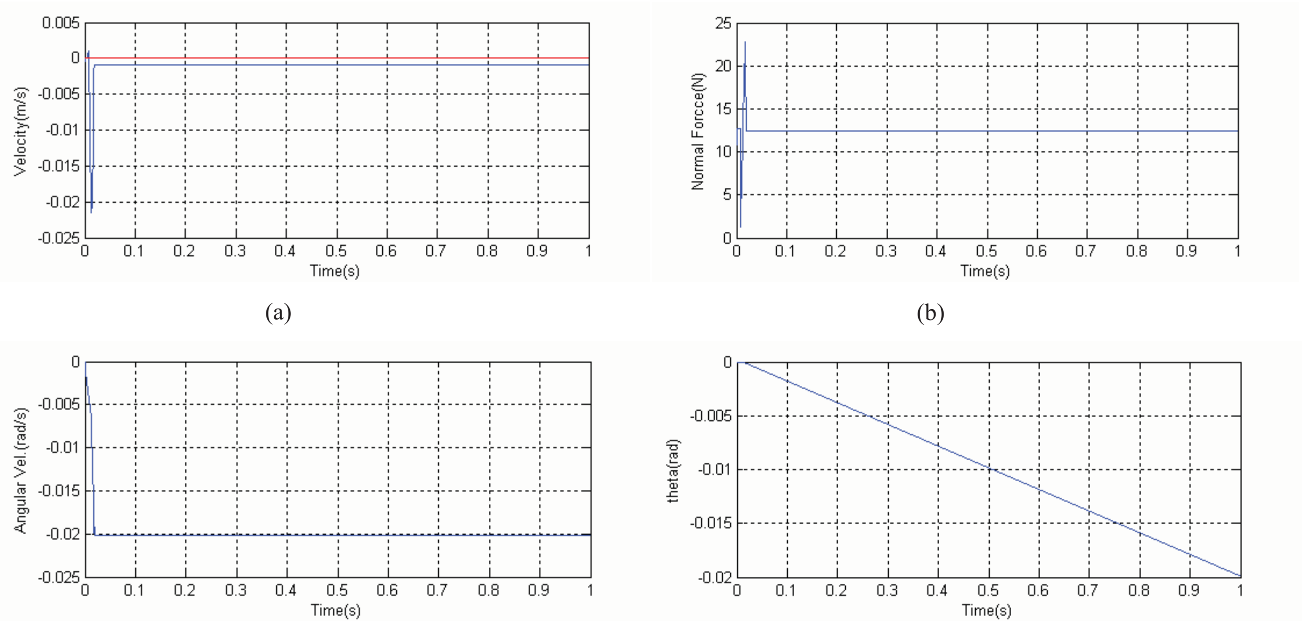


Figure 4 desired velocity

5 Conclusion

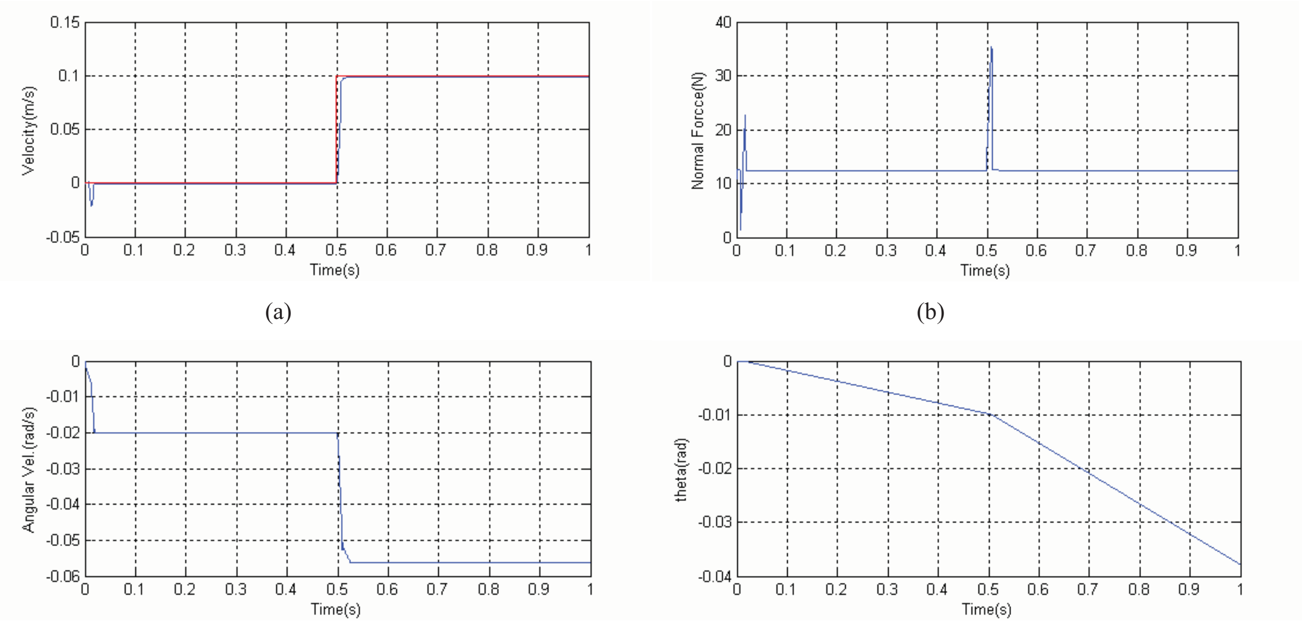
A mathematical model is developed which accounts for the effect of uncertainties of mass distribution of an object grasped by a two finger gripper. The model considers multi phase coulomb friction and introduces different patterns of friction forces, depending on different modes of motion. The model is employed to investigate robustness of a force-based control. The results show that the controller is robust in presence of mass uncertainties. The results also reveal that two-finger hand is not a good choice for safe grasping of objects with uncertainties in center of mass, and suggests use of a third finger or a multi segment fingers to reduce applied forces.



(a) (b)

(c) (d)

Figure 5 time history of motion of an object grasped by a two finger stationary gripper



(a) (b)

(c) (d)

Figure 6 time history of motion of an object grasped by a two finger gripper moving in y direction with a step increase in its speed.

6 References

[1] Shinoda, H. and Ando, S. A.: *Tactile sensor with 5-D deformation sensing*, in Proceeding of the IEEE International Conference on Robotics and Automation, Minneapolis, MN, USA, vol. 1, pp. 7-12, 1996.

[2] Jockush, J., Walter, J., and Ritter, H.: *A tactile sensor system for a three-fingered robot manipulator*, In Proceedings of the 1997 IEEE International Conference on Robotics and Automation, pp. 3080-6, 1997.

[3] Holweg, E. , Hoeve, H., Jongkind W.: L Marconi, C Melchiorri, and C. Bonivento, *Slip detection by tactile sensor: algorithms and experimental result*, In Proceeding of the IEEE international Conference on Robotics and Automation, Minneapolis, MN, USA, pp. 3234-9, 1996.

[4] Trembly, M. R., Packard, W.J., and Cutkoscy, M.R.: *Utilizing sensed incipient slip signals for grasp force control*, In Japan-USA Symposium on Flexible Automation, vol. 2, ASME, 1992.

[5] Glossas, NI. , and Aspragathos N.A.: *Fuzzy logic grasp control using tactile sensors*, Mechatronics, vol. 11, pp.899-920, 2001.

[6] Nakazava, N., Kim, I., Inooka, H., and Ikeura, R.: *Force control of a robot gripper based on human grasping schemes*, Control Engineering Practice, vol. 9, pp.735–742, 2001.

[7] Kim, I., Nakazava, N., and Inooka, H.: *Control of a robot hand emulating human's hand-over motion*, Mechatronics, vol. 12, pp.55-69, 2002.

[8] Birglen, L., and Gosselin, C.M.: *Grasp-state plane analysis of two-phalanx underactuated fingers*, Mechanism and Machine Theory, vol. 41, pp.807–822, 2006.

[9] Al-Gallaf, E.A.: *Multi-fingered robot hand optimal task force distribution Neural inverse kinematics approach*, Robotics and Autonomous Systems, vol. 54, pp. 34–51, 2006.

[10] Hadian, H., Keshmiri, M., and Sheikholeslam, F.: *A new approach on object slippage control in a cooperating manipulators system*, Proceedings of the ASME 2007 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, September 4-7, 2007, Las Vegas, Nevada, USA

[11] Lopez, J.A.D., Damper, R.I., Crowder, R.M., and Harris, C.J.: *Adaptive neurofuzzy control of a robotic gripper with on-line machine learning*, Robotics and Autonomous Systems, vol. 48, pp.93-110, 2004.

[12] Arimoto, S.: *Intelligent control of multi-fingered hands*, Annual Reviews in Control, vol. 28, pp.75-85, 2004.

[13] Ahmadi, H., and Sadigh, M.J.: *Safe Grasping in Presence of Multi Phase Friction*, 10 th International Conference on Control, Automation, Robotics and Vision, Hanoi, Victuam, P0608, Dec.2008.

[14] Sadigh, M.J., and Ahmadi, H.: *Robust Control Algorithm for Safe Grasping Based on Force Sensing*, proceeding of IEEE International Conference on Robotics and Biomatics, Bangkod, Thailand, P033, Dec.2008.