Forward

It is said that the hand is an agency of the brain. It reflects activities of the brain and thereby it is a sort of mirror to the mind.

Dexterity of the human hand is outstanding in comparison with that of apes. This difference comes from opposability of the human thumb to other fingers (index or/and middle fingers). Chimpanzee has a short thumb and a very long index finger, though Chimpanzee's DNA sequences resemble the most those of human DNA among all primates. Historically, mankind separated several millions of years ago from the apes who are intrinsically brachiators. Toward the end of brachiation the hand of apes has undergone a reduction in thumb length and an increase in finger length. In the process of evolution, mankind has acquired dexterity of the hand through perfection of such finger-thumb opposition. This can understood through Napier's book titled "Hands" [a], which was reviewed in such a way that:

> "Maybe Newton was right about the thumb [that it was evidence of God's existence], but there is far more to arouse wonder in the hand than he knew, and Dr. Napier indicates its scope with authority and imagination." — Eve Auchincloss, The New York Times Book Review

Although I could not pursue a further survey on how Isac Newton noticed the crucial role of human thumb, it is important for us to understand how such a morphological change of the human thumb evokes a remarkable progress of function of the hand. It is possible to refer again to Napier's book [a]

> "John Hunter's principle that "structure was the intimate expression of function" and that function was conditioned by the environment."

> "John Hunter turned our attention from the structure of the hand to its function, Charles Bell related the function of the hand to the environment, and Darwin demonstrated that the environment, by process of natural selection, gave birth to structure."

Dexterity of the hand has been investigated deeply and widely in developmental psychology [b] [c]. Observed data on infants fingering by all digits and pointing by the single index finger from the onset to the one year old birthday are collected and analyzed in details. On the other side, numerous multi-fingered hands mimicking the human hand have been designed and made in a number of universities and research institutes, in addition to sophisticated prosthetic hands with plural fingers. Notwithstanding such research developments, there is a dearth of research works on how such sophisticated mechanisms with multiple fingers with multiple joints execute a variety of everyday tasks in dexterous and versatile manners and what kinds of physical principles function in the process of task execution. In fact, until the end of the last millennium, there appeared none of explicit physical and mathematical models of dynamics expressing faithfully physical interactions of multiple fingers with an object including rolling contacts between them.

Pinching based on the finger-thumb opposition was first modeled in an explicit way by taking into account rolling contact constraints and flexibility of hemispherical finger ends in 1999 after the Head Investigator jointed the department of robotics, Ritsumeikan University, in 1997. In the academic years of 2001 to 2002 he was granted the Research Project, Grant in Aid for Scientific Research (C) (2) by the MECSST of Japan under the title: Dynamic stable grasping and object-manipulation by multi-fingered hands with soft tips based on sensory feedback (Project Number 13650290). Under this prior research project, our group derived an explicit expression of mathematical model for a pair of robot fingers with multiple DOFs and soft finger ends of hemispherical shape, which are pinching a rigid object. The model seems to be physically reasonable but too sophisticated to find any simple sensory feedback signal that may work well toward realization of stable pinching. During frequent discussions with Dr. course student, Miss Nguyen Anh (Now, Lecture of the Hanoi Institute of Technology), we discovered a simple and tractable form of sensory feedback signal easily calculated from the measurement data of joint angles and rotational angle of the object. Then, the effectiveness of this coordinated sensory feedback signal in realizing stable grasping was verified through computer simulation and experimental works by constructing an experimental setup composed of a pair of robot fingers with hemispherical soft tips. All these results were published during 2000 ~ 2002 in the literature that is listed below in References [1] ~ [10].

Under the present research project, we have treated stability of pinching motions under the assumption that finger-ends are of hemispherical shape but rigid unlikely from the previous research project. The reason is that theoretical treatments of the former case (soft finger-ends) were somewhat incomplete, in particular, in the case that the overall fingers/object dynamics are redundant in DOFs, though experimental works go easily and with better results. In the latter case (rigid finger-ends), geometrical constraints can be treated in a mathematically rigorous way. However, in the case that the total DOFs of the overall fingers-object system are redundant, there arise many possibilities of Equilibrium Point expressing a still state of secure pinching to which the system converges. In reality, those possible equilibrium points constitute a low-dimensional EP-manifold in the configuration space. Thus, we had to introduce a new concept called “stability on a manifold” and another concept called “transferability to a submanifold” (low-dimensional EP-manifold) and developed a rigorous analysis on stability of pinching motion on a constraint manifold embedded in the state space. Rigorously speaking, two-dimensional (planer) stable grasping in a dynamic sense can be interpreted in such a way that, given a concerned reference point in the state space of the closed-loop dynamics, there exists a neighborhood of it such that the solution to the closed-loop equation starting from any point in the neighborhood and lying on the constraint manifold converges asymptotically to the EP-manifold, that is, converges asymptotically to a certain still state belonging to the EP-manifold. All these theoretical considerations of stable grasping in this dynamic sense have been subsequently ascertained by a series of computer simulation based on the CSM (Constraint Stabilization Method) and experimental works on a variety of pairs of robot fingers with multiple DOFs. The most noteworthy outcomes under this project must be summarized in the following way: 1) "Blind Grasping" can function even in the case of a pair of robot fingers likely as human grasp an object even if they close eyes and 2) "Dexterity Analysis" can be done through introducing "dexterity index" and aiming at role-sharing among different joints of the thumb and index finger.

Our group is still struggling with extension of the present approach to cope with 1) Stable blind grasping in the case of arbitrarily-shaped objects, 2) Grasping in the case of arbitrarily-shaped convex finger-ends, and 3) 3-Dimensional stable grasping by means of two or more fingers with multiple joints moving in 3-D space. Each mathematical framework has already been made but verification has not yet been completed. Therefore, publication of the works will be carried forward in the next academic year.

It is quite fortunate for us to have fixed our eyes on a so-called Bernstein's Degrees-of-Freedom problem [d], or equivalently the problem of ill-posedness of inverse kinematics for redundant systems with excess DOFs. In fact, we have already dealt with dynamics with redundant DOFs in a proper way by introducing stability analysis on a constraint manifold. At the first time, we attacked a simple problem of multi-joint point-to-point reaching movements without any geometric constraint and thought that the problem might be solved without any difficulty as a byproduct of the previous approach that was successful in dealing with problems of stable grasping. The fact contradicts our first impression. We found through the vast literature published not only in the area of robotics but also in physiological journals that the problem of human multi-joint reaching is still controversial in neuro-physiology and, in particular, the problem in case of reaching movements with redundant DOFs still remain open to both areas of robotics research and physiology. The difficulty comes from nonlinearity of dynamics of human arm that is far dominant by 10^3 times than the case of human fingers, caused by differences of inertia moments between the upper or lower arm and each finger component. Thus, we applied for the Grant in Aid for Exploratory Research by the MECSST of Japan and were granted the research project titled "Resolution of ill-posedness of inverse kinematics for systems with redundant DOFs: A challenge to Bernstein's problem" (Project Number 16656085) for the three years of 2004 ~ 2006. The papers marked "＊" in the list of publications are more or less concerned with the subject of multi-joint reaching and therefore are not reprinted in this report. The paper marked "＊＊" are also excluded in this report to avoid duplication.

References 1

[a] J. Napier, *Hands*, Princeton University Press, Princeton, New Jersey (1993).

[b] C.L. Mackenzie and T. Iberall, *The Grasping Hand, North Holland, Amsterdam*, The Netherlands (1994).

[c] E. Thelen and L.B. Smith, *A Dynamic Systems Approach to the Development of Cognition and Action*, The MIT Press, Cambridge, Massachusetts (1993).

[d] N.A. Bernstein (translated from the Russian by M.L. Latash and edited by M.L. Latash and M.T. Turvey), *Dexterity and Its Development*, Lawrence Erlbaum Associates, Mahmash, New Jersey (1996).

References 2

[1] S. Arimoto, P.T.A. Nguyen, H.-Y. Han, and Z. Doulgeri, Dynamics and control of a set of dual fingers with soft tips, Robotica, Vol. 18, No. 1, pp. 71-80 (2000).

[2] S. Arimoto, K. Tahara, M. Yamaguchi, P.T.A. Nguyen, and H.-Y. Han, Principle of superposition for controlling pinch motions by means of robot fingers with soft tips, Robotica, Vol. 19, No. 1, pp. 21-28 (2001).

[3] S. Arimoto, Z. Doulgeri, P.T.A. Nguyen, and J. Fasoulas, Stable pinching by a pair of robot fingers with soft tips under the effect of gravity, Robotica, Vol. 20, No. 3, pp. 241-249 (2002).

[4] P.T.A. Nguyen and S. Arimoto, Computer simulation of controlled motion of dual fingers with soft-tips grasping and manipulating an object, Advanced Robotics, Vol. 16, No. 2, pp. 123-145 (2002).

[5] P.T.A. Nguyen and S. Arimoto, Learning motion of dexterous manipulation for a pair of multi-DOF fingers with soft-tips, Asian Journal of Control, Vol. 4, No. 1, pp. 11-20 (2002).

[6] Z. Doulgeri, J. Fasoulas, and S. Arimoto, Feedback control for object manipulation by a pair of soft tip fingers, Robotica, Vol. 20, No. 1, pp. 1-11 (2002).

[7] P.T.A. Nguyen and S. Arimoto, Dexterous manipulation of an object by means of multi-DOF robotic fingers with soft tips, J. of Robotics Systems, Vol. 19, No. 7, pp. 349-362 (2002).

[8] K. Tahara, M. Yamaguchi, J.-H. Bae, S. Nakamura, and S. Arimoto, Experimental results on dynamic stable grasping by a pair of robot fingers with soft tips, Proc. of the 2002 Japan-USA Symp. on Flexible Automation, July 14-19, Hiroshima, Japan, pp. 791-797 (2002).

[9] S. Arimoto, Can Newtonian mechanics explicate why and how babies (or robots) acquire dexterous hand motion?, Proc. of the 8th IEEE Int. Conf. on Methods and Models in Automation and Robotics (MMAR 2002), Sept. 2-5, Szczecin, Poland, pp. 129-136 (2002).

[10] S. Arimoto, J.-H. Bae, and K. Tahara, Dynamic stable pinching by a pair of robot fingers, Proc. of 2nd IFAC Conf. on Mechatronic Systems, Dec. 9-11, Berkeley, California, USA, pp. 731-736 (2002).