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Estimation of other's sensor patterns based on motion imitation and communication –Identification of symbolization strategy for sensor by comparative evaluation questions–

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***Abstract*— Estimation of user's sensorimotor patterns by motion observation enables robots to achieve user friendly supporting tasks. In previous works, we proposed a non user specific method to estimate other's sensorimotor patterns by a projection function between other's and self's sensorimotor experiences. Estimation errors derived from differences in body conditions were corrected by queries for sensory patterns. However, other's strategies how to symbolize for sensory patterns were not discussed. Thus, in this paper, we propose comparative evaluation queries for motions for this matter. With the method, the estimation for the other's torque patterns converged after a few queries with successful identifications. Feasible applications of the proposed method are not restricted only for the identification, but can estimate continuous sensory patterns that cannot be expressed by symbol representations.**

I. INTRODUCTION

One of the hard problems of intelligent robots which work in daily life environment is to understand user's intention. To understand user's intention, many methods have been proposed. For instance, observation of user's activity using video camera and rooms with sensor embedded floor with a use of RFID tags are proposed. However, estimation of inner states, such as whether a user would like to be assisted, is not easy to be estimated by these methods. It requires estimation of sensorimotor patterns of the user; it is an important basic technology for the purpose.

Several methods have been proposed to estimate tensional force on muscles with observation of a human's motion patterns by utilizing motion capture system and electromyography with detailed musculo-skeletal model of human's whole body[1][2]. Other methods using measurement devices of brain activities, such as fMRI, PET and EEG, have been also developed to estiamte what motor command a subject is trying to attempt. However, these methods require preparation of user specific musculo-skeletal model or avaraged brain activites in advance. In addition, these approaches cannot deal well with real environment where many users are expected to use in turn. Thus, we are interested in a flexible method that can estimate the sensorimotor patterns even in such real environment.

We propose an approach to estimate other's sensor patterns by a projection function between other's and self's sensorimotor experiences, in order to estimate sensorimotor patterns of the other's without predefined user specific model. By motion imitation with the projection function, the self could observe the other's sensorimotor patterns as if the self experienced that of the other's. Human beings, in daily life, are thought to estimate the other's sensorimotor patterns using the other's simulated experience by the projection function. This is called simulation theory[3], and this way, human beings could make the estimation flexibly.

This approach will work well if the self and the other have identical body conditions. However, it is natural that the conditions are different; estimation errors thus arises from the difference when the self makes the estimation based on the projection function between the sensorimotor experiences.

We have proposed a method[4] to clear this errors when using the approach of projection function, by communication and the mimesis model[5]. The general steps is outlined as follows.

1) The self and the other perform shared motions. From the motion patterns, the self estimates the other's sensory patterns using the mimesis model.
2) The both convert the sensory patterns to an expression call symbol-index, then exchange the expressions by communication.
3) The self uses the communication result in order to detect difference in the sensory patterns, then, modifies the mimesis model to have a better estimation of the other's sensory patterns.

a few repetition of these three steps resulted in a successful estimation of other's sensory patterns with 10%-20% errors[4].

However, there was a remaining problem, a symbolization strategy how to convert sensory patterns into the symbol-index was given for sake of simplicity. Intrinsically, the strategy is supposed to be unknown and it should change dynamically according to circumstances. Thus, it is required to estimate the unobservable symbolization strategy of the other. It is possible to estimate the strategy by the method in the previous work[4] if sets of motions and queries are prepared properly. However, it would require as same or more number of queries as of the strategy candidates. It is because the communication method used was a *open question* and there are almost infinite number of choices for the answers. When interactions between robots and humans

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are considered, it is better to limit the number of queries from the robot to the human and to reduce the possible choice of the answers. In other words, using *closed question* suits well for human robot interaction.

Thus, in this paper we propose a method, *comparative evaluation queries with motoins*, in order to have less amount of queries. In this method, the other was asked to perform two kinds of motions and answer which motion was heavier, or observed larger torque on joints. Expressing the comparison of the torque as an answer makes the method *closed question*. The *comparative evaluation queries with motoins* is used in the framework of the previous work[4] in order to estimate the intrinsically unknown symbolization strategy how to convert sensory patterns into the symbol-index.

In the second section, the mimesis model's properties and functions are explained followed by an explanation of the method in the previous work[4]. In the third section, the new method is explained. In the fourth section, an experiment using robots as an application of the proposing method will be explained and discussed. In the fifth section we finish the paper with conclusion.

II. Mimesis Model

A. General Properties

It is an engineering model of mirror neuron system[6][7][3]. The mirror neurons fire both when the subject observes a specific behavior and when the subject acts in the same manner. Findings in brain physiology suggestes that it describes relationship of the self and the other. Relationship between the mirro neurons and simulation theory[3] are also discussed.

The mimesis model abstracts sensory patterns $\boldsymbol{S}$ and motion patterns $\boldsymbol{M}$ of humans and humanoid robots. The abstracted representations called *proto-symbol* are calculated using Hidden Markov Models. A geometric space called *proto-symbol space* (PSS) is defined so that it expresses relationship of the proto-symbols as distances among static points x in the space. When a set of motor patterns $\boldsymbol{M}$ and sensory patterns $\boldsymbol{S}$ is defined as $\boldsymbol{O} = \ \boldsymbol{M} \ \boldsymbol{S}$, and a database of sensorimotor patterns is defined as $D = \ \boldsymbol{O}_1 \quad \boldsymbol{O}_n$, the PSS is represented by $P = F_{build}(D)$, where F_{build} is a function to construct the PSS from D. The distances between xs in the space are defined by both using Kullback-Leibler Divergence[8] to calculate distances between HMMs that correspond to the similarities of sensorimotor patterns, and using multi-dimensional scaling method[9].

B. Functions

The mimesis model offers following functions by utilizing the PSS. F_{recog}; a function to recognize sensorimotor patterns as a static point x in PSS, F_{gen}; a function to generate sensorimotor patterns from a x, an imitation function that outputs imitated sensorimotor patterns, and F_{assoc}; an association function that associates a partial sensorimotor patterns with a whole sensorimotor patterns even when only partial information is observed. Motion patterns can be also interpolated and extrapolated by creating internal/external dividing points of two proto-symbols in the PSS to define novel motion patterns[10]. In this way, the mimesis model can recognize and generate even unknown sensorimotion patterns, which are not in the database D.

C. Estimation of Sensorimotor Patterns

We realized the concept, which is an estimation of other's sensorimotor patterns by projection function between sensorimotor experiences of the self and the other, by using the mimesis model. We proposed a method with *open question* type communication to estimate the other's sensorimotor patterns in more precise manner, even if the body conditions are different in the slef and the other[4]. The outline of this process explained as follows and is depicted in Fig.1.

1) As an initial state, the self sets the other's inference model $\hat{P}_{other}$ based on own experience $D_{other} = \ \boldsymbol{S}_{self} \ \boldsymbol{M}_{self}$.
2) The self constructs $\hat{P}_{other}$ with $\hat{D}_{other} = \ \hat{\boldsymbol{S}}_{other} \ \boldsymbol{M}_{other}$ using F_{build}.
3) The other executes the shared motion $\boldsymbol{M}$ and observes corresponding $\boldsymbol{S}_{other}$. The self obtains $\hat{\boldsymbol{S}}_{other}$ from $\boldsymbol{M}_{other}$ using F_{assoc}.
4) Both the self and the other converts $\hat{\boldsymbol{S}}_{other}$ $\boldsymbol{S}_{other}$ into symbol-indexes k_{self} k_{other} respectively using a discretization function $F_{symbolize}$,
$$k_{self} = F_{symbolize}(\hat{\boldsymbol{S}}_{other}) \quad (1)$$
$$k_{other} = F_{symbolize}(\boldsymbol{S}_{other}) \quad (2)$$
The symbol-indexs are integers corresponding to strength of the sensor $\boldsymbol{S}$s.
5) The self modifies the $\hat{\boldsymbol{S}}_{other}$ in the $\hat{D}_{other}$ according to the result of exchange of the symbols k_{self} and k_{other}.
$$\hat{\hat{\boldsymbol{S}}}_{other} = \frac{k_{other}}{k_{self}} \hat{\boldsymbol{S}}_{other} \quad (3)$$
6) The self reconstructs $\hat{P}_{other}$ with the newly modified $\hat{\hat{D}}_{other} = \ \boldsymbol{M_{other}} \ \hat{\hat{\boldsymbol{S}}}_{other}$,
$$\hat{P}_{other} = F_{build}(\hat{\hat{D}}_{other}) \quad (4)$$

Steps through 3 to 6 are considered as single conversation set. The self adaptively acquires $\hat{P}_{other}$ with repetition of the conversation sets.

The remaining problem in the work[4] is that $F_{symbolize}$ was given. Intrinsically, the $F_{symbolize}$ is supposed to be unknown and it might change dynamically according to circumstances. In the next section, a method to estimate the other's $F_{symbolize}$ will be explained.

III. Comparative Evaluation Queries with Motions

In this section, we propose a communication method using *comparative evaluation queries with motions* in order the self to estimate other's symbolization strategy $F_{symbolize}$ how to convert sensory patterns to symbol-index. Choices of answers for the *comparative evaluation queries with motions*

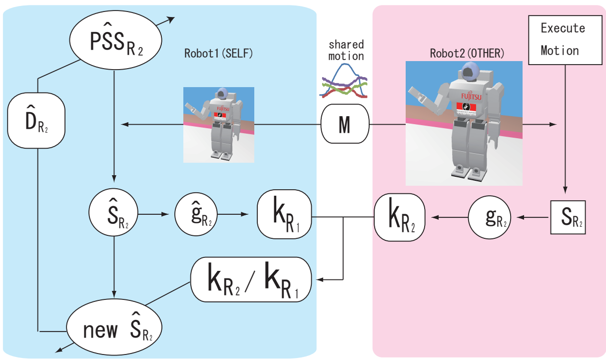

Fig. 1. Adaptive acquisition flow diagram of the other's proto-symbol space by open question

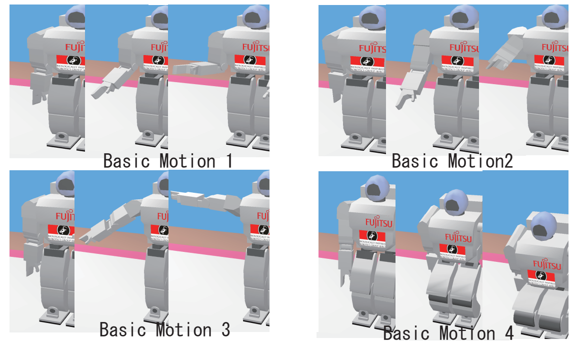

Fig. 2. Basic shared motion patterns for constructing PSS

are finite. For example, the answer could be either "yes" and "no". When the self attempts to estimate the other's $F_{symbolize}$, the self prepares more than two shared motion patterns. These motion patterns are designed specifically for the estimation of other's $F_{symbolize}$. The query of the *comparative evaluation queries with motions* is to ask for relative relationship of the observed sensory patterns for the motions. For example, an answer would be "Motion 1 is heavier". When there is an association function between sensorimotor patterns of the self and the other, this method can be applied to estimate continuous sensory patterns even if that cannot be expressed by symbol representation. The self can estimate the other's $\hat{F}_{symbolize}$ by following steps.

1) According to the identification target $F_{symbolize}$, the self prepares motion patterns $\boldsymbol{M}_i(i = 1\ 2)$.
2) The other imitates each $\boldsymbol{M}_i$ and observes corresponding sensory patterns $\boldsymbol{S}_i$.
3) The other converts $\boldsymbol{S}_i$ into scalar value g_i using conversion function $F_{symbolize}$.

$$g_i = F_{symbolize}(\boldsymbol{S}_i) \tag{5}$$

4) The other replies with a symbol-index K that tells the magnitude relation of the $g_1\ g_2$.

$$K = F_{comp}(g_1\ g_2) \tag{6}$$

That is, K is either "M_1 is heavier"('>'), "M_2 is heavier"('<') or "same"('equal').

5) The self identifies the other's $F_{symbolize}$ based on the replied symbol-index K.

If necessary, the self prepares a new set of motion patterns and repeats the steps above till identifies the $F_{symbolize}$.

IV. Application

For a validation of the proposing method *comparative evaluation queries with motions*, in this section, an application is introduced and an experiment is explained. The experiment of the application to solve a remaining problem in the previous work[4] is conducted. It is that the self estimates the other's symbolization strategy $F_{symbolize}$ that is unknown.

A. Conditions

The experiment involved two virtual humanoid robots HOAP-2 in a simulator environment. R_1 weighted 2 4[kg] as the self and R_2 weighted 4 8[kg] as the other were used. The masses were unknown to each others. Only symmetrical motions were used in the experiment, and considered joint angles are that of the right elbow, right shoulder's roll and pitch rotation and the right knee $\boldsymbol{\theta} = [\ _1\ _2\ _3\ _4]$. Considered joint torques were consisted of observed torques of the same joints $\boldsymbol{\tau} = [\ _1\ _2\ _3\ _4]$ respectively. The self prepared database $D_{R_1} = \ \boldsymbol{\tau}\ \boldsymbol{\theta}$ with four basic motions(Fig.2) for constructing proto-symbol space P_{R_1}.

As an association function F_{assoc} from $\boldsymbol{\theta}$ to $\boldsymbol{\tau}$, the R_2 observed the torque patterns $\boldsymbol{\tau}$ on the joints when R_2 performed the motions $\boldsymbol{\theta}$. In the experiment, we deal with estimation of $F_{symbolize}$ by R_1 identifying the conversion rule F_{conv} (Eq.(5)). It is because $F_{symbolize}$ is a composite function of F_{div} and F_{conv}, where the F_{div} divides input g into d equal segments and assigns symbol-index k based on TableI. This time the F_{div} was fixed and known to the self. As a discussion will be made in the section 6, estimation of the unknown F_{div} using the proposing method is possible and left for a future work.

TABLE I
RELATION BETWEEN SYMBOL INDEX AND VOCABULARY

k	d=3	d=5	d=7
1	light	light	very light
2	normal	bit light	light
3	heavy	normal	bit light
4	-	bit heavy	normal
5	-	heavy	bit heavy
6	-	-	heavy
7	-	-	very heavy

In this paper, following four conversion rules $f_i(i = 1\ \ 4)$ were prepared as candidates for the F_{conv} that converts joint torques($\boldsymbol{\tau}$) to an intermediate scalar value g.

- Average of all the torque patterns

$$f_1(\boldsymbol{\tau}) = \frac{\sum_j^J \frac{\int \ _j(t)dt}{T}}{J} \tag{7}$$

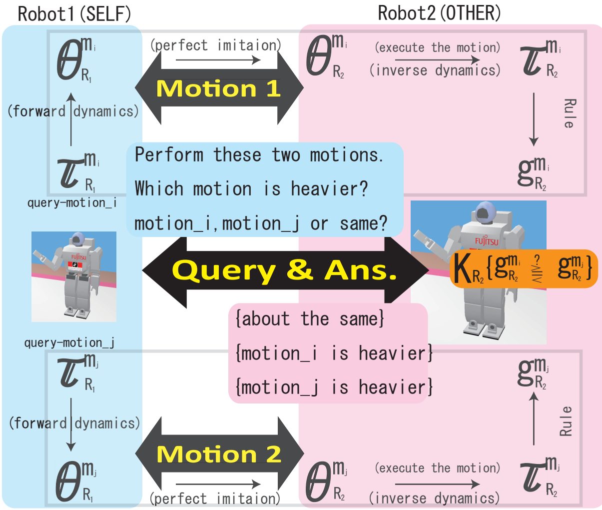

Fig. 3. Diagram of "comparative evaluation queries with motions"

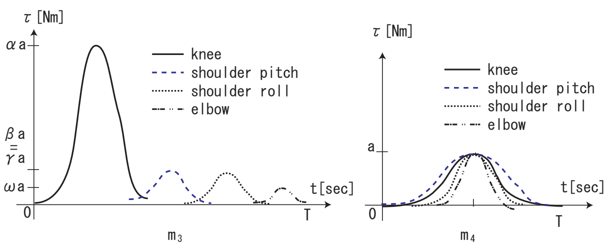

Fig. 4. Motion3 and Motion4 for the query2

- Sum of maximum values of each joint torques

$$f_2(\boldsymbol{\tau}) = \sum_{j}^{J}(\max_t \quad _j(t) \quad) \tag{8}$$

- Maximum value of composed joint torque patterns.

$$f_3(\boldsymbol{\tau}) = \max_t \sum_{j}^{J} \quad _j(t) \tag{9}$$

- Maximum value of maximum of each joint torques

$$f_4(\boldsymbol{\tau}) = \max_j \max_t \quad _j(t) \tag{10}$$

where T was the time period of $\boldsymbol{\tau}$. In this paper $J = 4$ was used.

B. Method

We explain how to design motion patterns and what queries makes the identification effectively. The flow of procedures is depicted in Fig.3. Two queries were prepared for the identification of the F_{conv}.

1) At first, R_1 makes query1 to identify whether $\hat{F}_{conv} = f_1$ or not. At query1, the R_1 uses two motions $m_1 \ m_2$ to execute query procedure explained in the section 3. R_2 imitates the motions($i = 1 \ j = 2$ in Fig.3). In order to identify whether $F_{conv} = f_1$, the m_1 and m_2 are designed so that maximum torques are differents but average torques over the same time period are the same.
2) The R_1 identifies $\hat{F}_{conv}$ based on the R_2's reply K. If $K =' \ . \ ,'$ then identifies as $\hat{F}_{conv} = f_1$, otherwise makes the next *comparative evaluation queries with motions*, and proceeds to query2.
3) The R_1 uses two motions m_3 and m_4(Fig.4) to execute query procedure explained in the section 3. At the query2, m_3 and m_4 were designed to identify the $\hat{F}_{conv}$ from $f_2 \ f_3 \ f_4$ at a time. The m_4(Fig.4) is a motion that the four joints bend and then stretch simultaneously, and the maximum torque are taken at the same time at the same value a. The m_3(Fig.4) is a motion that starts with a bending and stretching movement on the knee (a squat), followed by an up-and-down movement of the pitch rotation on the shoulder, followed by an up-and-down movement of the roll rotation on the shoulder, and ended with a bending and stretching of the elbow joint. The maximum values of each joint torque of the m_3 are $(\ a \ a \ a \ a)$. Constants a are required to meet the following conditions for the identification of the F_{conv}.

$$a < \quad < 4a \tag{11}$$

$$4a = \quad + \quad + \quad + \tag{12}$$

$$0 < \tag{13}$$

In this paper, $(\quad) = (3\ 0a \ \ 0\ 4a \ \ 0\ 4a \ \ 0\ 2a) \ a = 0\ 5$ were used.
4) The R_1 identifies $\hat{F}_{conv}$ based on the R_2's reply K. If $K =' \ . \ ,'$ then $\hat{F}_{conv} = f_2$, if $K =' >'$ then $\hat{F}_{conv} = f_4$, If $K =' <'$ then $\hat{F}_{conv} = f_3$.

It is assumed that the R_2 made perfect imitation of m_i performed by R_1, also assumed that the same conversion rule F_{conv} was applied to all the joints regardless of motion patterns.

C. Evaluation

In this paper, both R_1 and R_2 had identical body structures and mass density distribution with different amount of masses. The assumption that the R_2 imitates the motions of R_1 perfectly was taken. These conditions and assumptoin results in 100% successful identification of the conversion rule F_{conv}

To show the importance of identification of the F_{conv}, R_2's joint torques were estimated both with a successful identification of the F_{conv} and with an incorrect identification. 10 kinds of unknown motions $\boldsymbol{M'}_i (i = 1 \quad 10)$, which were different from the four basic motions, were introduced for the evaluation. These unknown motions consisted of arbitrary movement of the 4 joints. An error e between estimated torque $\hat{g}$ and the real g were defined as follows, using both known and unknown motions.

$$e = \frac{1}{N}\sum_{i}^{N}\frac{|\hat{g}_i \quad g_i|}{g_i} \tag{14}$$

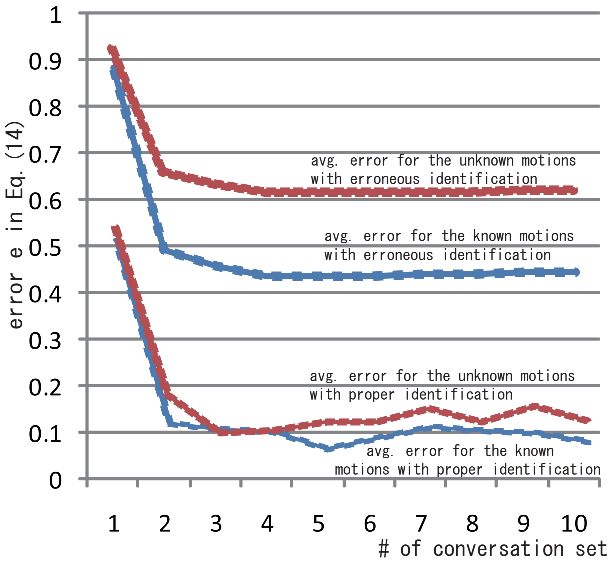

Fig. 5. Estimation results of torques of known and unknown motions when both successful and erroneous strategy identification when $d = 5$ and $F_{conv} = f_4$. The horizontal axis is number of conversation sets explained in section 2, and the vertical axis is the error e.

N was the number of motion patterns used for the evaluation. Experiment results when N=10 were shown in Fig.5. It shows, after a few set of conversation, that estimation of the other's torque can be achieved with approximately 10% error even if the motions are unknown. It also shows that errors are 45 60% for torque estimation when the identification of the $\hat{F}_{conv}$ failed.

The *comparative evaluation queries with motions* can estimate 3^N kinds of symbolization strategies by making qeuries with motions N times. This efficiency is important when the human robot interaction is considered, that is, the human can use the system without complex and large amount of preparation.

V. Conclusion

In this paper, we proposed a estimation method by *comparative evaluation queries with motions*. This enables robots to estimate 3^N kinds of symbolization strategies, how to convert torque patterns to symbol-indexes, by making queries with motions N times. The method consists of making queries with motions about unobservable sensory patterns, based on simulated other's experience that is calculated by projection function between experience of the self and the other. We think that the method is a fundamental interaction method for estimating other's unobservable inner information, such as sensory patterns.

This method is also thought to be useful to deal with the *correspondence problem*[11][12][13]. The *correspondence problem* is generally considered as a problem that deal with correspondence relationship between body parts of the self and the other. However, using the *query with motions*, it is possible not only to deal with motions, which can be shared between the self and the other, but also to deal with a new problem how to map between the self's sensory patterns and the other's unobservable sensory patterns.

In addition, with *comparative evaluation queries with motions*, it is possible to estimate continuous sensory pattern even when that cannot be expressed by symbol representations. The comparative evaluation of sensory patterns is an objective measure and the result is accurate, even when an estimation target sensor is other's unobservable one. Taking advantage of these properties, the proposed method can be applied, for instance, to estimate F_{div} defined at Table I and weight coefficient for each joints in Eq.(7)-Eq.(10).

Future works include estimation of the other's sensory patterns with the other's imperfect imitation, training method how to correct the other's imperfect imitation, estimation of information that cannot be expressed by scalar value such as line of sight and tactile information, estimations with different density distribution of the masses, and estimations with different DoF configuration of body structures.

References

[1] Gentiane Venture, Katsu Yamane, and Yoshihiko Nakamura. Identification of human musculo-tendon subject specific dynamics using musculo-skeletal computations and non linear least square. In *Proc. of the IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, pp. 211–216, 2006.

[2] Gentiane Venture, Katsu Yamane, and Yoshihiko Nakamura. In-vivo estimation of the human elbow joint dynamics during passive movements using musculo-skeletal model computations. In *Proc. of the IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, pp. 205–210, 2006.

[3] Vittorio Gallese and Alvin Goldman. Mirror neurons and the simulation theory of mind-reading. *Trends in Cognitive Sciences*, Vol. 2, No. 12, pp. 493–501, 1998.

[4] Tetsunari Inamura and Keisuke Okuno. Estimation of other's sensory patterns based on dialogue and shared motion experiences. In *International Conference on Humanoid Robots*, pp. 617–623, 2009.

[5] Tetsunari Inamura, Hiroaki Tanie, and Yoshihiko Nakamura. From stochastic motion generation and recognition to geometric symbol development and manipulation. In *International Conference on Humanoid Robots*, 2003. (CD-ROM).

[6] Giacomo Rizzolatti and Michael Arbib Language within our grasp. *Trends in NeuroScience*, Vol. 21, pp. 188–194, 1998.

[7] Merlin Donald. *Mimesis and the Executive Suite: missing links in language evolution*, chapter 4, pp. 44–67. Approaches to the Evolution of language: social and cognitive bases, Cambridge University Press, j. hurford and m. kennedy and c. knight edition, 1998.

[8] Solomon Kullback. *Information Theory and Statistics*. Wiley, 1959.

[9] Susan Schiffman. *Introduction to Multidimensional Scaling: Theory, Methods, and Applications*. Academic Press, 1981.

[10] Tetsunari Inamura and Tomohiro Shibata. Geometric proto-symbol manipulation towards language-based motion pattern synthesis and recognition. In *Proc. of Int'l Conf. on Intelligent Robots and Systems*, pp. 334–339, 2008.

[11] Aris Alissandrakis, Chrystopher L. Nehaniv, and Kerstin Dautenhahn. Imitation with alice: Learning to imitate corresponding actions across dissimilar embodiments. *IEEE Transactions on System, Man and Cybernetics -Part A: Sysmtes and Humans*, Vol. 32, No. 4, pp. 482 – 496, 2002.

[12] Verena Hafner and Frederic Kaplan. Interpersonal maps and the body correspondence problem. In *In Proceedings of the Third International Symposium on Imitation in Animals and Artifacts: Social Intelligence and Interaction in Animals, Robots and Agents*, pp. 48 – 53, 2005.

[13] Christopher Nehaniv and Kerstin Dautenhahn. *The correspondence problem. In Imitation in Animals and Artifacts*. MIT Press, 2002.