Human-Robot Communication with Hand-Clapping Language (Consideration from Communication Impedance Matching Viewpoint)

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***Abstract*— Conventionally, human-robot communication and robot-robot communication are dealt with in different manners in general. From the viewpoint of cooperation between human staff and robots as a heterogeneous group, however, it is natural and desirable that all of the communication within the group is performed based on a uniform communication manner. In this study, we deal with a communication method that can be adopted for both human-robot and robot-robot communication. We discuss a communication style by means of simple sound such as the hand-clapping. A communication language is introduced; the configuration of syllables, the words and their parts of speech and the syntax are discussed and designed from a general point of view. A perceptibility assessment is performed for the syllables. A preliminary experimental study is performed and the feasibility of the proposed human-robot communication style is examined. The concept of communication impedance matching is introduced as an analogy of the electric impedance matching. The feasibility of the proposed communication method is also discussed from this point of view.**

***Index Terms*— human-robot interaction, human interface, communication impedance matching, simple sound signal, communication, hand-clapping**

I. Introduction

Many of the robots currently developed for and adopted in practical applications are considered to be passive from the viewpoint of human-robot communication. For example, industrial robots such as manipulators or mobile robots are programmed to achieve the prescribed motion or given some commands corresponding to the task to be performed by themselves. It can be said that this is a kind of human-robot communication; such a communication is one way: from the human operator to the robots. Certainly, those robots also send some message or information back to the human operator in case. Most of such messages are, however, a kind of task completion results required to be sent beforehand; this kind of message-sending action is not a communication process but just a reaction, as a matter of fact.

Robots are coming out from the ideal world: laboratories and factories, to the real world: streets, schools and homes [1] [2]. In such a situation, a robot is expected to be an entity that is not only functional, but also socially interactive. One of the most important aspect of social interaction is communication [3], especially among a heterogeneous group consisting of robots and people around them [4]. Human-robot and robot-robot communication must be simultaneously taken into consideration.

From the viewpoint of efficiency of communication, it is natural that human-robot and robot-robot communications are performed in different manners [5]. The following case is a typical example: a communication style based on natural language and audio signal is adopted for the human-robot communication, while the wireless LAN system is adopted for the robot-robot communication. From the viewpoint of cooperation between human staff and robots as a heterogeneous group, however, it is natural and desirable that all of the communication within the group is performed based on a uniform communication manner. We discuss a uniform communication style applicable to both human-robot and robot-robot communications from this standpoint.

We deal with a communication method that can be adopted for both human-robot and robot-robot communication. We use a simple sound signal such as the beep or hand-clapping sound as the communication medium. The available information capacity is expected to be limited with this type of communication medium. On the basis of the communication medium, however, it is expected that the required signal processing for the robots can be simplified and realized at a low cost.

We discuss a communication language suitable to this type of medium. Basic consideration and a formal language specification are given. Human perceptibility for the designing hand-clapping language is examined based on a simple experiment by means of the beep sound.

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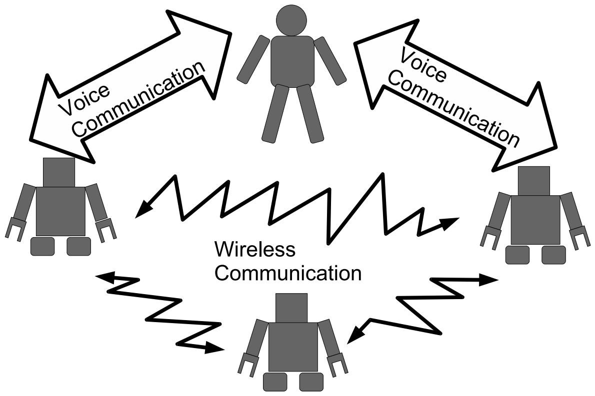
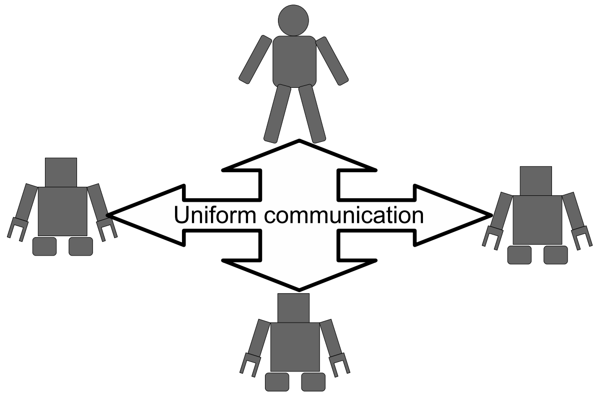


(a) Non-uniform style



(b) Uniform style

Figure 1. Conceptual sketch of two communication styles for human-robot and robot-robot communication

A preliminary experimental study of a robot having this type of communication interface is also performed with a simulation environment.

Not only the information capacity of the communication medium, but also the comfortableness or usefulness of the communication style for *both* human and robot should also be taken into consideration. A human and a robot have different communication characteristics; that is, their capability of signal and information processing is considerably different each other. We propose a means to evaluate this trade-off of comfortableness of a communication style between them in such kind of situation. We introduce a concept of communication impedance as an analogy of the electric impedance referring to the Ohm's law. Communication between a human and a robot by means of hand-clapping is discussed based on the concept of so-called impedance matching. The feasibility of the proposed human-robot communication approach is considered from the viewpoint of the communication impedance matching.

The paper is outlined as follows. First, we discuss the concept of the unified method for both human-robot and robot-robot communication in the next section. In order to realize the uniform communication style, we adopt simple sound signal such as the hand-clapping for the communication medium as observed in III, taking account of robots of relatively low-cost that are assumed to have low information processing capability. The hand-clapping language suitable to this kind of communication style is designed in IV. Experimental studies concerning the perceptibility and feasibility are conducted in V and VI. The significance of the proposed hand-clapping communication is discussed from the viewpoint of the communication impedance matching in VII. Finally, the concluding remarks in VIII summarizes the paper and indicates some future topics.

II. Uniform Human-Robot and Robot-Robot Communication

Many of the researches so far have dealt with human-robot communication from the viewpoint of a man-machine interface [6]-[8]. In such a case, the main concern about the communication method is its reliability and usability; that is, the intention or requirement of the user should be transmitted to the robot correctly and easily. On the other hand, the main focus of the current researches about robot-robot communication is not how to communicate, but what to communicate [9] or the purpose of communication [10]; that is, there are several communication devices already applicable to robot-robot communication such as wireless LAN system. Human-robot communication and robot-robot communication have been discussed from different aspects and dealt with in different manners.

Consider the case that a number of robots are performing a task under the supervision of a human manager or in cooperation with human staff as a heterogeneous group. In this case, each of the robots should communicate with the human manager or the human staff as well as its fellow robots. Certainly, human-robot and robot-robot communications can be performed in different manners. On the basis of such a non-uniform communication approach, however, the robots are required to have two types of communication devices corresponding to the human and the robot. They have to take care of the communication with the human staff and with the fellow robots differently even in the case that the meaning of the messages to be transmitted are identical for the both(Fig. 1(a)).

Unifying these communication methods for human-robot and robot-robot, the two communication systems adopted by each of the robots can be reduced to a single system. In this case, it is no need for them to distinguish the human staff and their fellow robots with regard to the communication(Fig. 1(b)). In addition, it is also possible for the human staff to grasp the contents of communication exchanged among the robots without premises. In such a case, the human staff can also directly interrupt and participate in the communication among the robots for confirmation or correction of their task, in the same manner as we join in a communicating human group.

III. Communication by Means of Simple Sound

Many kinds of human-robot communication systems or, in other words, human-robot interface systems have been developed so far and are currently under development. Each of these approaches has its own features. For example, the robot programming languages are generally not easy to use but able to give a detailed motion to be performed including such as conditional branches; the conventional teach-and-playback approaches are, on the other hand, not suitable to give a complicated motion but convenient for teaching relatively simple tasks; an approach based on hand-drawn sketch with a tablet [8] and a voice command approach based on a kind of simplified natural language [11] have a favorable usability for general people but are inferior in correctness of the transmitted commands and task specifications. Some of the communication or interface approaches are unidirectional. For example, the robot programming and teach-and-playback are used only for human to robot communication; conversely, many kinds of displays based on such as LC (liquid crystal), LED (light emitting diode) and CRT (cathode-ray tube) are widely used unidirectional communication devices from robot to human.

In order to realize the concept of uniform human-robot and robot-robot communication discussed in the previous section, an approach that is available for bidirectional communication between human and robot should be adopted. Theoretically, various communication media such as light, sound, radio wave, physical contacting, and so on are available for robots. The circumstances are the same for us, the human side; in the case of some of the media such as infrared rays or radio waves, however, we have to use some special devices in order to communicate by means of such media. Among the communication media, the audible sound is a promising candidate because not only both human and robot can easily use this communication medium but also it can be used for remote communication to some extent.

In the case of communication by means of audible sound, it is clear that voice communication based on a natural language is favorable for human users, especially for general people. For robots, on the other hand, hearing and understanding spoken natural language is not easy especially in the case that the speaker is an unspecified person. Syntax of a natural language is complicated and permits a certain degree of ambiguity in general; interpreting the message to obtain the meaning requires considerably cumbersome process. Simplification of communication style with audible sound should be considered from the viewpoint of its usability for robots.

An ultimate simplified style of sound communication is that based on simple sound such as beep or hand-clapping. Certainly, the available information capacity based on this simple communication style is limited; hearing, understanding and interpreting the message are, however, fairly easier for robots. The usability of this communication style is higher for a robot and lower for a human user compared to a natural language communication. As discussed in more detail in the later section, the authors consider that this situation is said to be well-balanced especially in the case of the communication taking place between human users and relatively simple robots, from the viewpoint of the difference in communication capability between them and the information capacity required for such kind of human-robot communication.

IV. Designing Hand-Clapping Language

On the basis of the above considerations, we deal with communication by means of simple sound. A well-known example of communication in such a style is the Morse code. It is, however, not immediately applicable to communication based on hand-clapping because of the requirement of the short and long sound elements (dot and dash) and not efficient because it requires many sound elements for each of the words. It is also difficult to interpret the received messages especially for robots of low computational capability in the case that the adopted communication method is based on a kind of natural language.

We design a prototype of communication language suitable to the situation taken into account, that is, the hand-clapping language. A natural spoken language consists of syntax and words; from the viewpoint of uttering and hearing, the words consist of one or more syllables in general. We discuss the formal points of view of the syllables, words and syntax of the designing hand-clapping language.

A. Syllable

From the viewpoint of uttering and hearing, a syllable is the smallest component of a language in general. We define a short series of hand-clapping or beep sounds as the syllable of the hand-clapping language in this study. There are a few candidates of configuration of such a syllable. One configuration example of a syllable is an expression simply in terms of the number of sounds included in the short series of hand-clapping. On the basis of this syllable configuration, however, the number of possible combination or the information capacity within a hand-clapping syllable under length constraint is extremely limited. For example, in the case that the length of the series of hand-clapping sound within a syllable is constrained to 8, the syllable can express only 8 patterns of messages consisting of 1 to 8 sounds; that is, the information capacity of such a syllable is 3 bits.

We introduce two types of intervals among a series of hand-clapping sounds corresponding to a syllable: short and long intervals. On the basis of the intervals, for example, a syllable consisting of 4 hand-clapping sounds has the information capacity of 3 bits; in other words, such a syllable can express 8 patterns of messages only by itself. In order to distinguish the short and long intervals within a syllable based only on itself in any case, we confine the syllables adopted in this study to those consisting of both of the two intervals. In this case, the number of message patterns that can be represented by a single syllable with the maximum length constraint 4 is 8. General form of the number of possible combinations N under the maximum length constraint n is given as

$$N = \sum_{i=3}^{n} (2^{i-1} - 2) \quad (1)$$

for this type of syllable configuration; that is, the numbers of possible combinations are 22 and 52 for the maximum length constraint 5 and 6, respectively.

B. Word

The richness of communication based on a language significantly depends on its available vocabulary. Similarly to natural languages, each of the words in our hand-clapping language can be consisting of one or more syllables. Since the number of possible single-syllable words is limited to 52 in case of the maximum length constraint 6 as mentioned above, multi-syllable words should be taken into consideration for vocabulary increase. Relatively short syllables are selected as prefix-syllables. These prefix-syllables are also used to classify the multi-syllable words; that is, the words in a specific category are designed to have the same prefix-syllable.

Since the number of available single-syllable words is limited, these words should be assigned for the meanings that are basic, important and frequently used. On the other hand, those multi-syllable words are a kind of optional; that is, they can be designed in accordance with the objective of communication required for the specific applications, respectively. For example, the words corresponding to such as ‘yes’ or ‘true’ that means affirmative, ‘no’ or ‘false’ that means negative, ‘to’ that indicates message receiver and ‘from’ that expresses message sender are designed to be of single-syllable.

C. Syntax

Because of its simplicity, the structure of a message expressed by means of the current hand-clapping language can be more properly referred to as a ‘protocol’ than as a ‘syntax’. Table I shows the syntax of the hand-clapping language dealt with in this study. In the table, the elements in square brackets can be omitted. In the case that the receiver is omitted, the destination is assumed as *all*; in the case of the sender that is omitted, it is assumed as unknown. The elements in parentheses are alternative. The elements in italic, *to*, *from* and *all* are corresponding to specific single-syllable words, respectively.

The predicate is the main part of the message. Basically, the message represents a requirement or a command that is to be performed by the receiver; there is no need to describe the subject, that is, the one performing the given requirement or command. As shown in the table, the parts of speech to be prepared for the designed hand-clapping language are as follows:

proper noun
: These indicate the name or identifier attached to each of the robots and human staff.

TABLE I.
SYNTAX OF HAND-CLAPPING LANGUAGE

message	[receiver] predicate [sender]
receiver	*to* (proper-noun, $\cdots$ | *all*)
sender	*from* proper-noun
predicate	(verbal-phrase | adverbial-phrase)
verbal-phrase	verb [noun-phrase] [adverbial-phrase]
adverbial-phrase	(adverb | preposition noun-phrase)
noun-phrase	([adjective] noun | pronoun | proper-noun)

pronoun
: The use of pronoun enriches the message expressed by the language and is convenient for us. It is difficult for robots, however, to identify the intended object corresponding to the given pronoun especially in the case that they have limited sensing devices or low computation capability. On the basis of the consideration, the only pronoun assumed in the current hand-clapping language is ‘me’ that indicates the message sender itself.

noun
: These are used to represent various general items. A special word denotes the all robots and human staff participating the communication, ‘all’, is also taken into consideration.

verb
: These represent various situations, motions, commands, and so on. The existence of the corresponding direct or indirect object depends on the meaning of the verbs.

adverb
: These are general adverbs. A message consisting of a single adverb, such as ‘yes’ or ’no’ is available in the designed hand-clapping language.

preposition
: These are also taken into account; the most two important prepositions are ‘from’ and ’to’ that indicate the sender and the receiver, respectively.

adjective
: These are general adjectives. The applicable adjectives highly depend on the sensing capability of the robots; for example, in order to use the word such as ‘red’ or ‘blue’, the robot must have the ability to distinguish these colors.

It is noted that what kind of words to be prepared for each of these parts of speech is significantly depending on the objective of communication.

On the basis of the syntax, the shortest messages can be represented only by a single word such as

“Stop”

to all of the robots and human staff from an anonymous sender.

V. PERCEPTIBILITY ASSESSMENT OF SYLLABLES

From the viewpoint of the perceptibility, robots and humans have different kinds of problem with this type of communication method. For robots, one of the important

TABLE II.
PERCEPTIBILITY OF SYLLABLES
(MAXIMUM LENGTH CONSTRAINT: 6)

Syllable No.	Syllable Pattern	Error (%)	Syllable No.	Syllable Pattern	Error (%)
1	+ ++	0	27	+ ++ +++	30
2	++ +	3	28	++ + +++	15
3	+ +++	0	29	+ + + +++	12
4	++ ++	6	30	++++ ++	12
5	+ + ++	9	31	+ +++ ++	30
6	+++ +	0	32	++ ++ ++	9
7	+ ++ +	6	33	+ + ++ ++	24
8	++ + +	21	34	+++ + ++	9
9	+ ++++	15	35	+ ++ + ++	27
10	++ +++	9	36	++ + + ++	33
11	+ + +++	6	37	+ + + + ++	24
12	+++ ++	3	38	+++++ +	24
13	+ ++ ++	21	39	+ ++++ +	21
14	++ + ++	15	40	++ +++ +	24
15	+ + + ++	0	41	+ + +++ +	18
16	++++ +	9	42	+++ ++ +	24
17	+ +++ +	9	43	+ ++ ++ +	33
18	++ ++ +	12	44	++ + ++ +	48
19	+ + ++ +	24	45	+ + + ++ +	9
20	+++ + +	6	46	++++ + +	24
21	+ ++ + +	18	47	+ +++ + +	33
22	++ + + +	15	48	++ ++ + +	21
23	+ +++++	21	49	+ + ++ + +	48
24	++ ++++	15	50	+++ + + +	6
25	+ + ++++	18	51	+ ++ + + +	33
26	+++ +++	0	52	++ + + + +	24

issue is to distinguish the specific hand-clapping or beep sound used for communication from the background noise; the differentiation of short and long sound intervals within the syllables is not significant problem for them. On the other hand, it is not significant matter for us to distinguish the specific hand-clapping or beep sound from the background noise in general; however, we have some difficulty in perceiving and differentiating the short and long intervals in order to identify the correct syllable. This is considered to be because our short-term memory is not always accurate in some case.

In order to examine human perceptibility for the hand-clapping language communication, we conduct the following experiment with 11 human subjects:

1) Generate all patterns of the syllables under the maximum length constraint 6.
2) Each of the patterns is randomly presented to the human subject with the beep sound; the subject answers the perceived syllable by means of the computer keyboard.
3) Repeat 1 and 2 three times for each of the subjects.

The adopted short interval is randomly selected between 200 and 300 ms for each of the human subjects and the long interval is its double. The obtained result is shown in Table II.

On the basis of the result of this perceptibility experiment as shown in Table II, it can be said that longer syllables tend to be of lower perceptibility. There are, however, syllables of relatively high perceptibility consisting of 6 sounds such as '+++ +++' (No.26) and '+++ + + +' (No.50); that is, the perceptibility does not simply depend on the length of the syllables but also depends on its complexity of the combination of short and long intervals.

It is also noted that 19 out of the 52 possible patterns of syllables of maximum lengths constraint 6 have perceptibility error ratio of less than 10% based on the results of this experiment. In addition, there are another 11 syllable patterns having perceptibility error ratio of less than 20%. On the premise of some ask-back process, these syllables can be also available. In some application [11], required number of basic message patterns can be less than 20; most of the frequently-used words can be of single-syllable as well as high perceptibility in such a case.

VI. PRELIMINARY EXPERIMENTAL STUDY

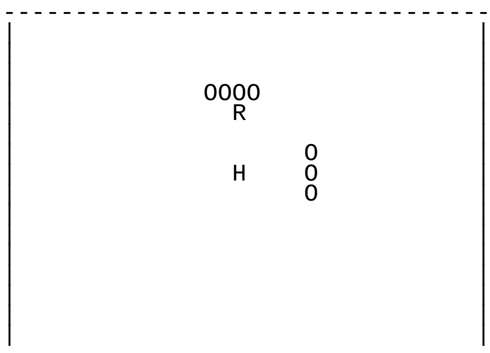
A preliminary experiment for this type of communication style is conducted with a simulated simple 2D mobile robot and a hand-clapping interface.

A. Experimental System with Simulated 2D Mobile Robot

Fig. 2 shows the simulated 2D mobile robot adopted in this experimental study; a robot 'R' is placed in 16×32 lattice field equipped with the home position 'H' and the obstacles 'O'. Messages from the human operator to the simulated robot are transmitted via the experimental hand-clapping interface shown in Fig. 3; messages from the robot are transmitted by means of the beep sound of the computer system that is adopted for this simulation.

The hand-clapping interface board detects sound signals simply based on a predetermined threshold level and measures the time intervals among them. In the current interface system, sound characteristics such as the frequency or waveform pattern are not taken into consideration.

The simulated robot is assumed to be able to move in any of the four directions. Touch sensors are also assumed for the robot; that is, it can detects an obstacle in the moving direction.



R: Mobile robot H: Home position O: Obstacles

Figure 2. Simulated simple 2D field with mobile robot

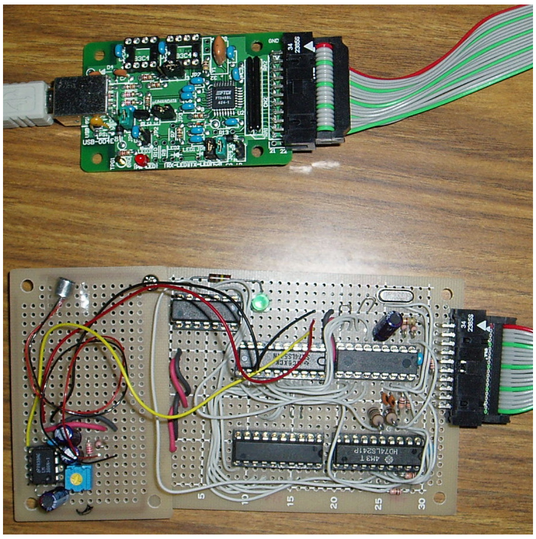


Figure 3. Experimental hand-clapping interface board

B. Implementation of Hand-Clapping Language

On the basis of the basic design in IV and the perceptibility assessment in V, the hand-clapping language for the simulated 2D mobile robot is implemented. Table III shows the list of the words adopted in the current implementation. In this implementation, all of the adopted 24 words are of single-syllable. The perceptibility and the regularity are taken into consideration for the selection of sound pattern. For example, the numbers: One: '+++ +', Two: '+++ ++' and Three: '+++ +++' and the names: Human 1: '+ +++ +' and Human 2: '+ +++ ++' well represent the regularity of the selected sound pattern. Short syllables of low perceptibility error ratio are assigned to the most important words such as Yes: '++ +', No: '+ ++' and Stop: '+ +++'. Three robots and two human colleagues are assumed in this implementation; however, in the current experiment, we deal with only one to one human-robot communication.

C. Preliminary Communication Experiment

We conduct communication experiments by means of the simulated simple 2D mobile robot and the hand-clapping language interface. Fig. 4 shows a typical example of such communication. In this example, the robot found something (we know that is an obstacle placed in the field) and report the situation to the operator. Message elements corresponding to the sender and the receiver are omitted because the communication is performed in one to one manner.

The current experiments are performed in a quiet well-conditioned situation without environmental noise. Communication by means of short messages consisting of a few words is performed relatively well. However, even a short message of two or three words, we have to confirm what it means after we hear it, by means of the word list shown in Table III, especially in the early period; the communication situation is cumbersome from this view point.

TABLE III.
IMPLEMENTED HAND-CLAPPING LANGUAGE

Pattern	Part of speech*	Meaning
++ +	adv.	Yes/Positive/Accept
+ ++	adv.	No/Negative/Reject
+++ +	n./adj./prop.	One/Robot 1
++ ++	prep.	To
++ + +	prep.	From
+ +++	v.	Stop
+ ++ +	v.	Start
+ + ++	v.	Move
++++ +	n.	Something
+++ ++	n./adj./prop.	Two/Robot 2
+++ + +	n.	Step/Block
++ +++	adv.	Forward
++ ++ +	adv.	Left
++ + ++	adv.	Right
++ + + +	adv.	Backward
+ ++++	n.	Nothing
+ +++ +	prop.	Human 1
+ ++ ++	pron.	Me
+ + +++	v.	Exist/Found
+ + + ++	n./adv.	Home
+++ +++	n./adj./prop.	Three/ID.3
+++ + + +	v.	Request help
++ ++ ++	n./adj.	All
+ +++ ++	prop.	Human 2

* prop. = proper-noun / pron. = pronoun / n. = noun / v. = verb / adv. = adverb / prep. = preposition / adj. = adjective

Human:	+ + ++ [Move]	++ +++ [Forward]	
Robot:	++ + [Accept]		
Robot:	+ + +++ [Found]	++++ + [Something]	++ +++ [Forward]
Human:	+ +++ [Stop]		
Robot:	++ + [Accept]		

Figure 4. Example communication by means of hand-clapping language

On the basis of the preliminary experiments, it becomes clear that such communication style requires the expertness of the human operator. Usability consideration from the human viewpoint has to be taken into consideration for the language design.

VII. COMMUNICATION IMPEDANCE MATCHING

As demonstrated in the previous section, the human-robot communication by means of hand-clapping is considered to be possible; however, it is not so easy for a human to use the hand-clapping language. Conversely, for a robot having poor signal processing capability and limited information processing capability, it is not so easy or often very difficult to communicate with human by means of a general spoken natural language.

Which kind of communication method should we use for human-robot and robot-robot communication in a uniform manner, human-friendly or robot-friendly? In this section, we give a preliminary consideration on this problem from the viewpoint of communication impedance matching.

A. Communication Impedance as an Analogy of Electric Impedance

We deal with information transmission among individuals that have different communication characteristics each other. The human-robot communication is a typical example.

In this preliminary consideration, we adopt the following simple model of information transmission based on a specific communication method. For each of the individuals taking part in the communication, we assume the characteristic relation expressed as

$$I = C_i V_i, \tag{2}$$

where I denotes the transmitted information, C_i is the communication capability of individual i by means of the specified communication method and V_i is the effort required for individual i to accomplish the communication. Introducing the quantity $R_i = 1/C_i$, (2) is rewritten as

$$V_i = R_i I. \tag{3}$$

This equation represents the Ohm's law of electric circuit in the case that V_i is the voltage, R_i is the impedance and I is the electric current. That is, the quantity R_i in (3) is interpreted as the communication impedance. Equation (3) now expresses the following interpretation of communication:

> The effort required to perform the communication is the product of the transmitted information and the communication impedance of the individual for the specified communication method.

Consider two individuals 1 and 2 are to communicate with each other by means of a specific communication method. Their impedance values for the communication method are respectively R_1 and R_2. We assume that the total effort available for their communication is limited to $V = V_1 + V_2$. The corresponding electric circuit is shown in Fig.5. On the basis of the Ohm's law on the series circuit, the transmitted information and the effort required for each individual are expressed as

$$I = \frac{V}{R_1 + R_2}, \tag{4}$$

$$V_i = R_i I. \tag{5}$$

Equation (4) represents that the transmitted information is determined by the sum of the communication impedance of the both individuals.

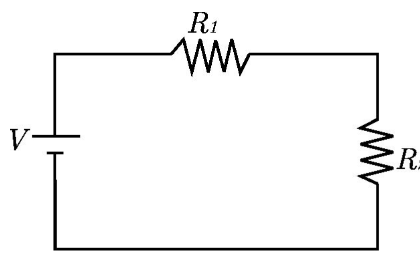


Figure 5. A circuit with two impedance devices

In the case of communication between heterogeneous individuals such as dealt with in this study, their communication capability for a specific communication method is considered to be significantly different in general. We assume the case that individual 1 has significantly greater communication capability as follows:

$$C_1 \gg C_2 \qquad \text{i. e.} \qquad R_1 \ll R_2. \tag{6}$$

On the basis of (4), it is clear that the improvement of communication capability of individual 1, the superior one, does not significantly contribute to the improvement of the overall performance of information transmission; the communication capability of individual 2 should be improved.

B. Utility of Transmitted Information and Impedance Matching

As an analogy of the power in electric circuit, we introduce the following quantity as the *utility* of transmitted information for each of the individuals:

$$P_i = V_i I = R_i I^2 = \frac{V^2}{R_i}. \tag{7}$$

This quantity represents a criterion that regards information transmitted with more effort as more valuable.

On the basis of the introduced utility, consider the case that individual 2 receives information from individual 1. The electric circuit representation of the situation is the series circuit shown in Fig.5. We discuss the following problem:

> By means of a specific communication method such that the communication impedance of individual 1 is specified, maximize the utility of obtained information of individual 2 by adjusting its communication impedance.

The mathematical representation of the problem is expressed as

$$\begin{array}{ll} \text{Maximize } P_2 & \text{with respect to } R_2 \\ & \text{subject to } V_1 + V_2 = V \ . \end{array} \tag{8}$$

According to the theory of impedance matching, the well-known solution to this problem is $R_2 = R_1$; that is, it is suitable that the receiver has the same impedance as the sender. This indicates the concept of communication impedance matching.

C. Hand-Clapping Communication from the Viewpoint of Communication Impedance Matching

Currently, robots have low communication capability for a natural spoken language in general; that is, their communication impedance is high in such a case. The situation is conspicuous especially for robots of relatively low cost that have poor signal processing capability and limited information processing capability. In contrast to that, the human communication impedance for such a spoken language is obviously extremely low. Consider the case of human-robot communication by means of a natural spoken language. The information transmitted by the human-robot communication is limited because the total communication impedance becomes high due to the high communication impedance of the robot. The utility of information obtained by both human and robot in this case is also small; this is especially true for the human, because his/her effort for the communication is extremely low compared to the robot.

From the viewpoint of the communication impedance matching mentioned above, it is considered that the difference in communication impedance between human and robot should be reduced. That is, the situation can be improved by lowering the communication impedance of the robot. This is performed by adopting a robot-friendly communication method. The corresponding human communication impedance is expected to become higher in this case; however, because of the intrinsic high information processing capability, the human communication impedance is expected to be kept at lower level compared to the robot to communicate with, especially in the case of the low-cost robot having limited information processing capability. This turns out to be increase in the transmitted information as well as its total utility.

The human-robot communication by means of the hand-clapping language dealt with in this study is a kind of robot-friendly communication style. The usability of the communication method for human is not so good. From the viewpoint of the communication impedance matching discussed above, however, the approach is considered to be a promising candidate for human-robot communication. The communication impedance of human and robot in this case becomes respectively higher and lower than in the case of sound communication based on a natural spoken language. The difference in communication impedance between the human and the robot is significantly reduced. That is, the hand-clapping approach can improve the total utility of transmitted information of the human-robot communication.

VIII. Concluding Remarks

Social interaction among humans and robots is one of the important topics for the robots that operate in close proximity to human society. For such socially interactive robots, one of the key issues is the human-robot communication. In this study, we deal with the issue from the viewpoint of a uniform communication method that is available for human-robot as well as robot-robot communication.

Taking account of the applicability to relatively simple robots, we discuss a communication style by means of simple sound, i. e. the hand-clapping language. The formal language specification is developed; we discuss the configuration of syllables, the parts of speech of the words and the syntax of the message expressed in the hand-clapping language. Perceptibility assessment of the possible syllable patterns is conducted. A preliminary feasibility examination of the proposed communication approach is also performed by means of the simulated 2D mobile robot and the prepared hand-clapping interface. The obtained result indicates that the human-robot communication with simple sound such as hand-clapping or beep sound is possible by means of the designed hand-clapping language; it should be also noted, however, that the expertness of the human operator is significant for the communication.

Human-robot communication in a uniform bidirectional manner is also discussed from the viewpoint of human-friendliness and robot-friendliness of the adopted communication method. The concept of communication impedance matching is introduced as an analogy of the electric impedance matching. On the basis of the discussion, it can be said that a robot-friendly communication method such as the proposed hand-clapping language is a promising candidate for human-robot communication, especially in the case of robots of low information processing capability.

We do not take account of the background noise in the current experiment. Consideration on such a noisy situation is one of the important topics of the communication method of this type. An ask-back procedure can be a primitive remedy for this problem; however, the effect should be evaluated. Experimental study dealing with the communication between a human operator and two or more robots is also a key issue from the viewpoint of uniform human-robot and robot-robot communication style. These topics are left as the future works.

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