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Force based Manipulation of Jenga Blocks

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Abstract— **Our goal is to copy human dexterity of manipulation with force feeling to robot manipulation. We adopt Jenga game as our first target task. This paper describes our strategic implementation how robot removes blocks from Jenga tower. In this paper, we make Jenga kinematics model. First we show kinematics model of stable Jenga tower. Another kinematics model is of transition period of removing block. Using these kinematics models, robot manipulator chooses the most safe block to remove. But of course, there exist difference of acting force between ideal model and actual Jenga tower. So the robot judges the acting force against ideal one whether the block can be removed or not. When it is judged not to remove, the robot changes to next candidate to remove. According this force based manipulation strategy, the robot has achieved to remove more than twelve blocks form Jenga block tower. During competition with human, the robot can remove a block after more than twenty blocks are removed.**

I. Introduction

Recently, there are many production processes which are realized by robot manipulators. But there still exist many tasks which can be done by human but cannot be done by robot manipulators. Human beings use their arms and fingers to achieve several complex tasks. Especially, human operators are strong for tasks which use dexterous sensing at their fingertip. This dexterity may be achieved not only by fingertip sensing and fine motion, but also by fusion of visual sensing and high diagnosis. In this study, we would like to consider possibility of implementation this kind of dexterity to robot manipulator. Especially, we pay attention to dexterity of force based manipulation during object handling.

We adopt Jenga game[1] as our first target task. Jenga is a game for human. It requires quite dexterous manipulation since sometimes even human player misses to manipulate. But the task is very simple. So we think it is good benchmark task for dexterity of robot manipulation.

In this paper, we first introduce Jenga game and show some previous robotics researches. In Section 2, we introduce a kinematics model of stable Jenga block tower. In Section 3, we introduce another kinematics model during removing block. Based on these models, we show our strategy of removing block in Section 4. The experimental system is shown in Section 5 and the results are in Section 6. With discussion in Section 7, we conclude in Section 8.

A. Jenga Game

In Jenga game, 54 wooden blocks are stacked as a tower with 18 layers. Each layer has 3 blocks. Between neighboring two layers, the blocks are perpendicular to each other. A player removes an arbitrary block and puts it on the top of the block tower. If the tower looses its balance and fall to pieces, the player looses the game. Here, it is not allowed to remove a block from the top two layers.

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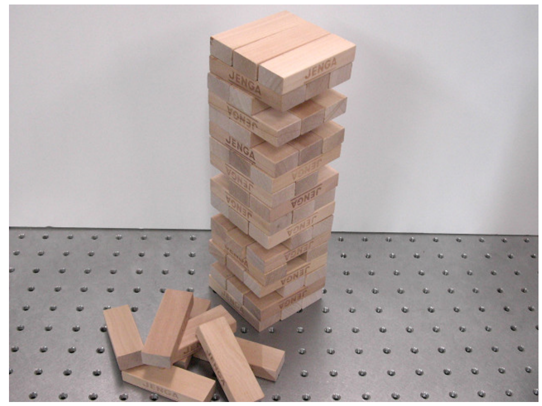

Fig. 1. Jenga block tower

In actual play, size of blocks have dispersion. So there exist both of easily removable blocks and blocks hard to remove. Since mass of blocks also have dispersion, even if a player operate according to ideal models, block tower may fall. This uncertainty makes Jenga game interesting.

B. Playing Jenga

The rule of Jenga game is like as above. Next, we observed strategy how human player acts for Jenga block manipulation in actual game. Human player sees and imagines which block seems to be removed easily. After decision, the player tries to remove the block, while he senses the reactive force whether it is too large and he also looks the block tower whether it will break down. It requires very dexterous manipulation with force and visual sensing. Even human may miss the manipulation. It is very nice and interesting benchmark of robot dexterous manipulation.

C. Related Works

There exist some researches which show Jenga block removing by robot manipulator. Kroger et al.[2] introduces a manipulator with a stereo vision sensor, a 6-dof force/torque sensor and a laser range sensor. This manipulator had succeeded to remove 29 blocks. The robot chooses a block randomly and pushes the block. If it senses large force or look the tower leans, the robot changes to another block randomly. Wang et al.[3] also uses a vision sensor. By the vision sensor, robot checks a motion of other blocks during removing a block and achieves safe extraction. Shinoda et al.[4] uses omni-directional vision system to find status of Jenga tower and remove a block by a multi-fingered hand.

They are not about Jenga block manipulation, there exist some researches to manipulate multiple objects such as Aiyama et al.[5], Harada et al.[6], Donald et al.[7] etc. The researches by Aiyama and Harada, kinematics model of acting force between multiple objects is made and robot manipulators are controlled to realize stable grasping of multiple objects according to the model. However in Jenga manipulation, robot manipulator is not allowed to approach more than two blocks. So it cannot plan to achieve stability of the whole objects.

II. Kinematics of Jenga Block Tower

In this paper, we introduce kinematics model of Jenga block tower and strategy to find a block to remove easily. But actually, there exist some errors between ideal models and actual phenomenon. So we introduce block changing strategy with force sensing during removing block. With this strategy, a robot manipulator can remove a block safely.

A. Stable Pattern of Tower Layer

First, we checked a model of stacked blocks. We pay attention to stability of one layer of block tower and its support by the lower layer. Combinations of the lower layer must be one of the five patterns in Fig. 2. In the view point of simple status of multiple blocks, Fig. 3 is also stable. But, according to Jenga game rule, it cannot be achieved. Before building this pattern the tower must be broken. So, here, we make a kinematics model of these five patterns with forces from upper layer and calculate acting force to the layer.

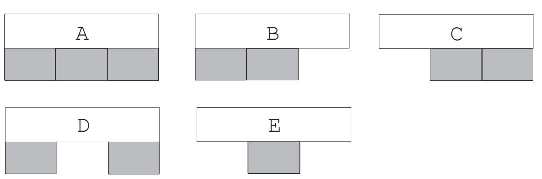

Fig. 2. Five patterns of Jenga tower layer

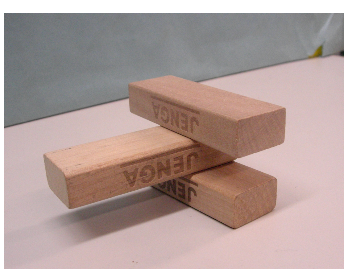

Fig. 3. Impossible pattern under Jenga rule

B. Kinematics of Layer

To calculate acting force to all blocks, we start its analysis from top layer to lower layers step by step.

First, we set some assumptions. As modeling of ideal state of block tower, we consider that all blocks have same size ($W \times W/3 \times H$), mass (M) and coefficient of friction (μ), which are all known. As preliminary experiments, we check mass and coefficient of friction for 4 sets of commercial Jenga block. The variation of the parameters between different sets is relatively large, however the variation between blocks in same set is relatively small. So we think it can be considered that these parameters are same in the same set. We also assume that the center of gravity of each block locates at the center of the block.

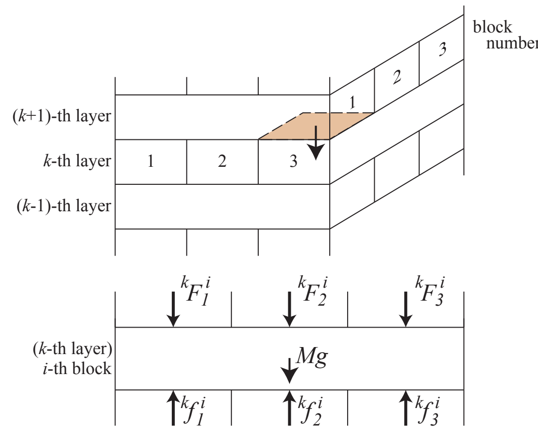

Fig. 4. Force model acted on a block

Now, we analyses forces acted on one block in k-th layer. We set that a model of acting force between upper and lower layers is located on the center of contact face. as shown in Fig. 4. For balance of the block,

$$\begin{gathered} {}^kF_1^i + {}^kF_2^i + {}^kF_3^i + Mg = {}^kf_1^i + {}^kf_2^i + {}^kf_3^i \\ {}^kF_1^i - {}^kF_3^i - {}^kf_1^i + {}^kf_3^i = 0 \\ {}^kf_1^i \geq 0, \quad {}^kf_2^i \geq 0, \quad {}^kf_3^i \geq 0 \end{gathered} \tag{1}$$

If there are no blocks j in the upper or lower layers, ${}^kF_j^i = 0$ or ${}^kf_j^i = 0$. ${}^kF_j^i$ are known since the upper layer is already analyzed. So, we should analyze ${}^kf_j^i$ from the above equations. If there exist solutions f_j^i, this block is stable.

However, in cases such as Fig. 5, the above model cannot reply stable solutions. In such cases, we divide acting force from the center lower block as shown in Fig. 5. Two forces ${}^kf_{20}$ and ${}^kf_{21}$ are acted on the both edge of the contact face. These cases may occur to pattern B, C and E in Fig. 2. So,

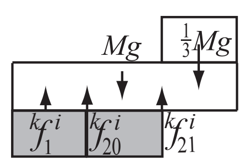

Fig. 5. Modifying kinematics model of center block

first we analyze with the f_2 model. If it is not stable, we analyze again with f_{20} & f_{21} model. If it replies a stable solutions, the block is stable.

There exist another condition to be considered. Eq. (1) has two conditions. But in pattern A and pattern B and C with f_{20} & f_{21} model, there are three forces. These are indeterminate cases. So here, we define ${}^kf_j^i$ as that stress of each contact face is close to each other.

With these models, ${}^{k}f_j^i$, acting force between the layer in attention and the lower layer can be calculated. When we pay attention to the next $(k-1)$-th layer, we set

$$^{(k-1)}F_i^j = {}^{k}f_j^i. \quad (2)$$

When we use f_{20} & f_{21} model,

$$^{(k-1)}F_i^2 = {}^{k}f_{20}^i + {}^{k}f_{21}^i.$$

From this process, we can obtain the all force acting on the whole block tower.

III. Kinematics of Removing Block

In this section, we introduce another kinematics model. The model is of transition period of removing one block. With this model, we can find the best block to remove.

A. How to determine removing block

First of all, when we consider a block to remove, the tower must be stable after the block is removed. It means that the tower without the attention block must be stable. But, even if the tower after removing is stable, there is a case that the tower falls to pieces during removing the block. This is caused by friction force. It acts to move other blocks together. So in this section, we define margins of stable during removing operation. With these margins, removing block will be determined.

When a robot removes a side block, direction to remove can be considered as 3 direction as shown in Fig. 6. Removing to A and C direction occur moment to rotate the tower blocks. Under static friction condition, an object is easier to rotate than to slide. So, this situation should be avoided. Then in this process, we set that a robot remove a side block to B direction.

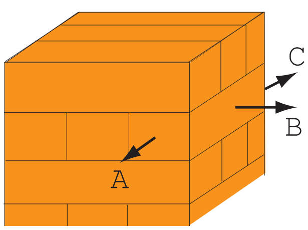

Fig. 6. Removing direction condition

When removing a center block, a robot choses from direction A and C by stability of the tower with the margins.

B. Upper block margin

When a robot tries to remove a block, there is some cases that other upper blocks are also pulled by friction from the target block as shown in Fig. 7.

We define upper block stability margin $f_{umargin}$ as gap between f_{slide}, maximum static friction force between removing block and upper blocks and f_{stay}, maximum static friction force between other block in the same layer and upper blocks; $f_{umargin} = f_{stay} - f_{slide}$. It should be $f_{umargin} > 0$ and when $f_{umargin}$ becomes large, the upper blocks are hard to be pulled by the removing block. If $f_{umargin} < 0$, the upper blocks will be pulled with the

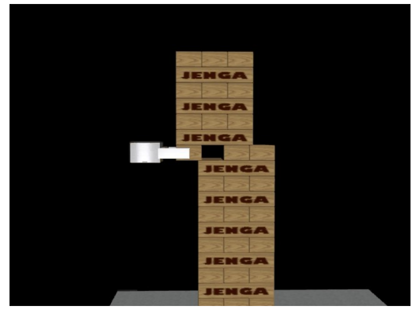

Fig. 7. Miss removing by upper blocks

removing block. So, to avoid such cases as Fig. 7, a robot should select a block which has large margin $f_{umargin}$.

While removing block i in k-th layer, acting force on upper blocks are as Fig. 8. f_{slide}, f_{stay} are as Eq. (3) and (4).

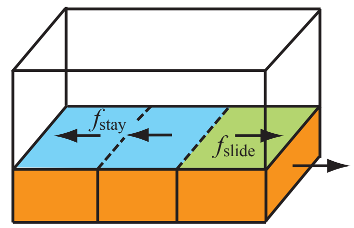

Fig. 8. Acting force when upper blocks moving right

$$f_{slide} = \sum_{j=1}^{3} \mu \, {}^{k}F_j^i \quad (3)$$

$$f_{stay} = \sum_{h=1, h\neq i}^{3} \sum_{j=1}^{3} \mu \, {}^{k}F_j^h \quad (4)$$

So the upper block stability margin of block i in k-th layer is defined as

$$f_{umargin}^{k,i} = f_{saty} - f_{slide}. \quad (5)$$

C. Lower block margin

Another case of failure during removing block is as Fig. 9. The tower tilts and is broken at the lower block under the removing block.

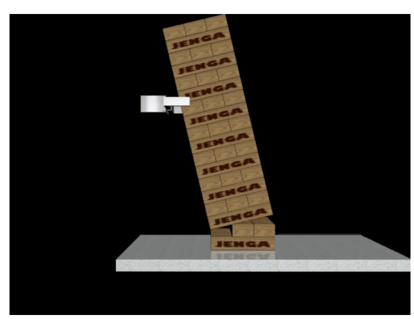

Fig. 9. Miss removing by lower blocks

To avoid this case, we define lower block stability margin. Here we regard blocks to tilt as one body. This body will brake and tilt at lower edge of a certain layer (q-th layer). In this case, minimum force to tilt this body at k-th layer is calculated as f_{fall}^q. The maximum friction force between grasped block and the rest body is as f_{pull}. With these forces, the lower block stability margin is defined as $f^q_{lmargin} = f^q_{fall} - f_{pull}$. It should be $f^q_{lmargin} > 0$ and when $f^q_{lmargin}$ becomes large, the body is hard to tilt and break. If $f^q_{lmargin} < 0$, the lower body will tilt and break at q-th layer. So, to avoid such cases as Fig. 9, a robot should select a block which has large margin for all $q = 1, \cdots, k-1$.

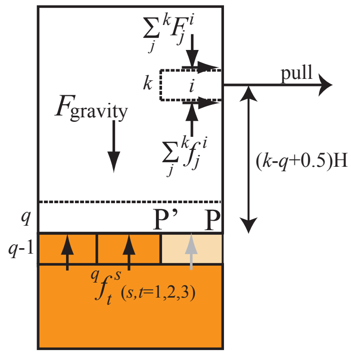

Fig. 10. Force acting on block body

Rotation center of block body at q-th layer is differ if there exists a block in $(q-1)$-th layer as shown in Fig. 10. If there is a side block, rotation center may be P. In the other case, P' will be rotation center. To obtain moment around P or P' by gravity force, mass and position of center of gravity of the body is required but they are not obvious. Then, we use other force which is balanced with the gravitational moment. It is a set of contact forces between $(q-1)$-th and q-th layers.

When the block body tilts at q-th layer by pulling a block i in k-th layer, we set $d^{k,i}_{q,s,t}$ as a distance between rotation center P or P' and every contact force ${}^q f^s_t$.

$$f^q_{fall} = \frac{1}{(k-q+0.5)H} \sum_{s=1}^{3} \sum_{t=1}^{3} {}^q f^s_t d^{k,i}_{q,s,t} \tag{6}$$

$$f_{pull} = \sum_{j=1}^{3} \mu \, {}^k F^i_j + \sum_{j=1}^{3} \mu \, {}^k f^i_j \tag{7}$$

So the lower block stability margin of block i in k-th layer is defined as

$$f^{k,i}_{lmargin} = \min_{q \in [1,k-1]} f^q_{lmargin} = \min_{q \in [1,k-1]} \left(f^q_{fall} - f_{pull} \right) \tag{8}$$

IV. Strategy for Removing Block

A. Candidate block for removing

Conditions for blocks to be removed is as analyses in previous sections; (1) the block tower must be stable after target block will be removed, (2) during removing block, two margins $f_{umargin}$, $f_{lmargin}$ must be positive. Blocks which satisfy these conditions can be candidate block to remove. Here, we will select the best block as the largest margin block.

Now we consider an integrated margin;

$$f^{k,i}_{margin} = \frac{f^{k,i}_{umargin} f^{k,i}_{lmargin}}{f^{k,i}_{umargin} + f^{k,i}_{lmargin}} \tag{9}$$

A block which has the largest margin will be the candidate block to be removed. But, as shown in next subsection, we need second and third candidate. So we set these next candidate as for the margin.

B. Judgment of removing possibility

The strategy in the above subsection is based on ideal model such as block size, mass, friction etc. Actual block has small dispersion. Sometime block tower may tilt and bend to certain direction. So some blocks may not have contact force from its upper blocks. Some blocks may have larger contact force from its upper blocks.

This means that there should exist some error between model force and actual force. Then when a robot tries to remove a block, it senses actual force by force sensor. By comparing the actual force with model force, it decides the block can be removed safely or not. If it decides that the block cannot be removed, then the robot changes removing block to next candidate. With this strategy, the robot will remove a block which is seems to be removed.

C. Gripper for Jenga block removing

We have developed a gripper for Jenga block removing. It has small 3-axis force sensors at its jaws as shown in Fig. 11. When it grasps a side block, it grasps like as Fig. 12. When it removes a center block, first it pushes a block by nail as shown in Fig. 13, and then grasps as shown in Fig. 14.

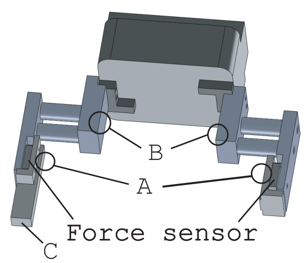

Fig. 11. Design of gripper for removing Jenga block

V. Experimental Setup

A. Equipment

According to the strategy above, we have developed a manipulation system to removing Jenga blocks. Yaskawa MOTOMAN-UPJ, a 6-d.o.f. manipulator with 6-axis force/torque sensor at its wrist is used. As an end-effector, an air-gripper with jaws shown above is attached.

This manipulator is a small one, so it cannot approach to back side of block tower. So we introduce a rotary table which is moved by human operator. Robot program orders to human operator which face should be in front of the robot. The whole system is as shown in Fig. 15.

This system cannot re-grasp a block and then cannot put removed block on the top of the tower. So, human operator represent to put the removed block on the top. After that, human operator input the place with keyboard.

When the system and a human player play competition, the robot cannot find which block the human player removed

Fig. 12. Grasping side block to remove

Fig. 13. Pushing center block

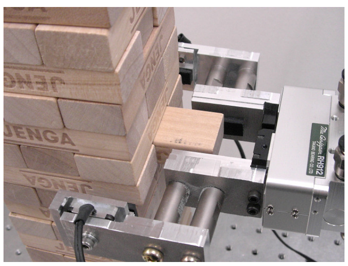

Fig. 14. Grasping center block after pushing

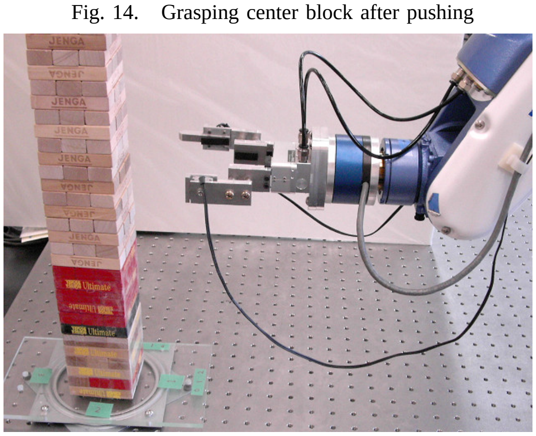

Fig. 15. Experimental equipment

and where he/she puts it on. So, human operator also input the removed block and set place with keyboard.

To avoid collision between a manipulator and a table, some blocks (red, black etc.) are piled on the rotary table. They are fixed to the rotary table not to break during manipulation.

When the robot grasps a block, its position and posture must be known. But, block pose may have some errors. At that time, human operator helps its small modification to close position of the block.

B. Advance measurement of friction

We should set coefficient of static friction in kinematics model. We did advance measuring experiment of friction force before Jenga block manipulation.

Here, blocks are made from wood, there may be difference according to direction. So, we tested both of width direction and depth direction. Farther, coefficient could be changed according to temperature and humidity, We should measure just before manipulation.

On the target block, we put blocks one layer (3 blocks) to 16 layers for each step. To two direction, we measured 18 times for every pattern. Mass of one layer is measured as 38.5[g]. From this measurement, we obtain μ_{wdir}=0.211 and μ_{ddir}=0.216 as coefficient of friction to width and depth direction respectively. So we consider there is no difference depend on block direction. Then, in this time, we set coefficient of friction as 0.213 for experiment.

C. Threshold for avoidance to break

In our strategy, we decide whether a robot removes a block or not according to difference between ideal model and actual force. So, we must set a certain threshold for abandonment.

Here, we use the manipulator with a 6-axis force/torque sensor, which measures reaction force during removing block. From several arbitrary formed block tower, the manipulator removes a block in several position. We compare these results with ideal model force.

The comparison result is shown in Fig. 16. Green circles mean successful removing and red triangles mean failures.

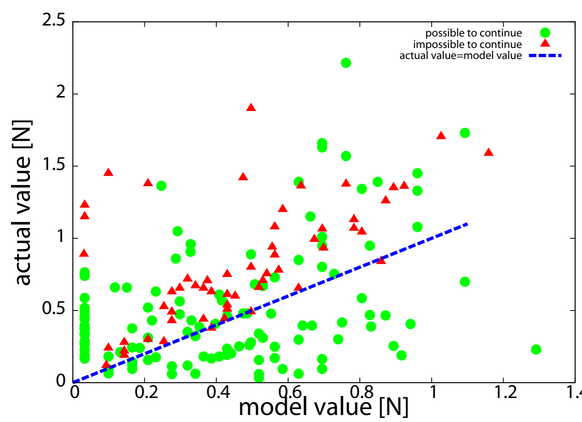

Fig. 16. Removing result with ideal and actual acting force

From the results, we can find that when actual force is smaller than the modeled value, almost all removing are successfully achieved. If the actual force becomes larger than the modeled value, it may succeed or it may fail to remove. From this, we set the threshold for changing candidate block as the same as modeled value. During operation, if the force sensor measures larger force than modeled value, the robot gives up the first candidate block and changes to the second one, the third one, and so on.

If there is no block which acting force is smaller than the threshold, the robot elevate the threshold slightly and return to the first candidate again.

VI. Experiment Result

A. Removing by robot

With the equipment, we did some experiments. First one is removing only by robot manipulator. In the previous research of Wang[3], they evaluate their system by number of successfully removed blocks by removing only by a robot. So, we also count the number of removed blocks before tower breaking or failure of operation.

Putting a block on the top of the tower after removing is done by human operator according to robot order. If there is no blocks on the top layer, a block should be put at the center. In other case, the robot orders random position from both side.

The result of 20 trials is shown in Fig. 17.

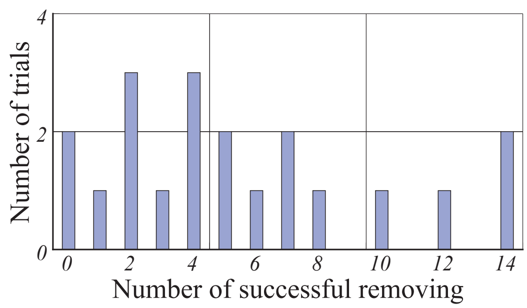

Fig. 17. Result of removing by robot manipulator

B. Competition with human player

The second experiment is competition by robot manipulator and a human player. As same as the first experiment, games are continued until breaking tower or failure of operation. Where human player removes and where he puts the block on are entered with keyboard. With this input, the robot recognize current situation of block tower.

The result of 16 trials is shown in Fig. 18.

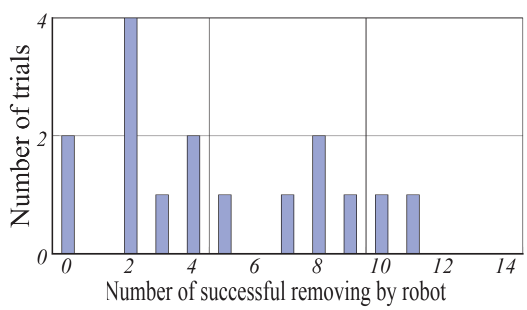

Fig. 18. Result of competition by robot manipulator

In all of these 16 trials, the game is finished by robot failure. But, when we did not record the experiment operation, the robot won to human player with removing 13 blocks.

VII. Discussion

In research of Wang[3]et al., 8 blocks in 9 layers are candidate of removing. In their experiment with 20 trials, maximum number of removed block is 5 and average is 2.7. It may not be fit to compare this result and our result because of different approaches (vision based and concentration to force), but our result seems to be good for the task. In particular, it is very regrettable that we did not record, but it is very impressive that the robot won to human player.

From these results, we consider, it is a good approach for some dexterous manipulation methods to make kinematics models and to modify with actual force which is observed.

But, we have to pay attention to one point. From the result graphs, there are some failures at very few number of blocks like as 0 or 1. It is not happened to human players.

Almost all cases of failure is by moving upper blocks together as shown in Fig. 7. We have to check precisely kinematics model. But, it may be hard to recognize whether upper blocks moves together or not after it starts to move. The reacting force may not be different so much. So it may be hard to sense only by force sensors.

In the future, we should use vision sensor, range sensor etc. And we should develop modification strategy of kinematics model parameters; when the robot measures a certain force at a certain place, acting force in the whole block tower may be modified with the information.

VIII. Conclusion

In this paper, we have develop Jenga kinematics model. We showed kinematics model of stable Jenga tower and another kinematics model during removing block.

Using these kinematics models, robot manipulator chooses the most safe block to remove. But since there exist difference of acting force between ideal model and actual Jenga tower, the robot judges the acting force against ideal one whether the block can be removed or not. When it is judged not to remove, the robot changes to next candidate to remove.

According this force based manipulation strategy, the robot has achieved to remove more than twelve blocks form Jenga block tower. During competition with human, the robot can remove a block after more than twenty blocks are removed.

It is a good approach for some dexterous manipulation methods to make kinematics models and to modify with actual force which is observed. After this research, we will try other applications. There are several tasks which requires human dexterity like as force sensing, fine motion, etc. For example, parts assembly with very precise insertion with very small gap between peg and hole, metal-carving with very precise impact force, and so on.

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