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First human–robot archery competition: a new humanoid robot challenge

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Abstract

A humanoid robot developed to play multievent athletes like human has paved a way for interesting and popular robotics research. One of the great dreams is to develop a humanoid robot being able to challenge human athletes. Therefore, the challenge of humanoid robots to play archery against human is organized at Taichung, Taiwan, in HuroCup, FIRA 2018, on August 7th. The difficulties of developing humanoid robot are not just on playing archery. The humanoid robots for HuroCup must make use of the same hardware for the 10 events. In this paper, the design and implementation of the humanoid robot for archery are proposed under the trade off with other nine events. Therefore, the humanoid robot must have some special design and development on software. More specially, the humanoid robot must use professional bow to challenge human for archery competition. Therefore, in this paper, special shooting posture under constrained arm structure and motion planning of both arms for more torque to play professional bow are proposed. In addition, the further development of humanoid robot to improve archery shooting is summarized.

1 Introduction

After industrial robots (e.g. robot arms) became popular products, many societies and associations tried to find the next focus of robot research. Over two decades ago, an obvious trend is to introduce robots into human life, for example, service robots, accompany robots, and so on. However, in human life, the robot research and development must face many difficulties that are extremely different from the industrial robots in the uniform environment such as factory. The robot developed in human life is not just technique problems. Friendly, safety criterion, and so on are other more important issues. Therefore, Federation International of RoboSport Association (FIRA) and RoboCup (https://www.robocup.org/) proposed robot competition and challenge from 1996. FIRA builds the website http://www.firaworldcup.org/ to promote robot competition and challenge. The robot competition and challenge push on a growing way for robot research and development in human life.

One of the major objectives of FIRA and RoboCup is to have a robot soccer team fighting and winning FIFA championship team on 2050. The further goal is to develop innovative robot techniques that are applied in human life. FIRA and RoboCup build a benchmark platform to solve the problems of robotics research and boost development progress based on competition and challenge. The matches between the teams of robot soccer and human are excitedly interactive between robots and human. In recent years, FIRA association extended further objective to sport, not just soccer. For example, HuroCup in FIRA includes 10 events, basketball, climbing, lift and carry, long jump, obstacle run, sprint, weight lifting, archery, marathon, and united soccer. The participant teams must make use of same humanoid robot

Table 1 The world record of HuroCup on kid-sized sprint. (Note that from 2009, the distance is extended to 3 m.)

Date	Event	Team	Affiliation	Time
July 2003	World Cup, Vienna, Austria	Manus	National University of Singapore	01:05.00 seconds
July 2004	World Cup, Busan, Korea	Manus	National University of Singapore	00:27.00 seconds
July 2006	World Cup, Dortmund, Germany,	Manus	National University of Singapore	00:25.00 seconds
16th June 2007	World Cup, San Francisco, USA	Pie	Tamkung University, Taiwan	00:24.00 seconds
23rd July 2008	World Cup, Qingdao, China	aiRobot	National Cheng Kung University, Taiwan	00:20.00 seconds
20th Aug. 2009	World Cup, Incheon, South Korea	H.I.T.	Harbin Institute of Technology	01:07.50 seconds
30th Aug. 2011	World Cup, Kaohsiung, Taiwan	Team Plymouth	University of Plymouth, U.K.	00:42.00 seconds
25th Aug. 2012	World Cup, Bristol, U.K.	Red Atom	Nanyang Polytechnic, Singapore	00:29.02 seconds
18th Dec. 2016	FIRA World Cup, Beijing, China	Ichiro 1	Institut Teknologi Sepuluh Nopember Surabaya, Indonesia	00:21.18 seconds

hardware to autonomously finish the 10 events. The long-term objective of this league is to develop full capability humanoid robots.

In FIRA, HuroCup attracted many international teams to focus on humanoid robot research for this competition, such as Snobots from University of Manitoba, Canada, Plymouth from University of Plymouth, United Kingdom, aiRobot from National Cheng Kung University (NCKU), TKU from TamKang University (TKU), and so on. In addition to joining HuroCup, many teams published their research results. For example, Team NCKU developed different walking gaits for stable and fast walking of humanoid robots (Li *et al*., 2015, 2017). Team TKU developed the algorithms for object recognition and pose estimation (Lin *et al*., 2018). For strong fighting capability during the competition, team TKU humanoid posture correction for developed push recovery balance control (Liu *et al*., 2019). As a result, HuroCup competition challenged humanoid robot technology to push research forward.

Anniversary FIRA attracts many respecters to enjoy robot competition together. It is a kind of robots in human life, and under control in much safety. Sometime, the organizers arrange some special activities for robots to be more interactive with the respecters. The special activities thus stimulate the focus on developing humanoid robots to challenge human athletes, such as sprint and marathon. HuroCup started on 2002 and entered the period of explosive growth from 2007 to 2011. Many participating teams published research results based on competition experiments.

The technique of humanoid robot continuously progresses from anniversary world cup. The technique improvement can be concluded by the records of world cup. For example, as shown in Table 1, the world record of sprint in kid size, based on the competition rule (Baltes *et al*., HuroCup Sprint Rule), is improved quickly. From start, the distance of sprint is only 2 m. The humanoid robot needs to complete forward and backward traces for the 2-m distance. On 2008 World Cup, the record time is reduced to 20 seconds. Therefore, the distance is extended to 3 m on 2009. On 2016, the time is improved to 21.18 seconds. Similarly, based on the competition rule (Baltes *et al*., HuroCup Marathon and weight lifting rules), the marathon world record is improved, as shown in Table 2, and the weight lifting world record is improved by 80 disks on 2016. HuroCup competition actually improves the technique of humanoid robots. On 2018, a very surprising result occurred on weight lifting. The world record of

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Table 2 The world record of HuroCup on kid-sized marathon

Date	Event	Team	Affiliation	Time
17th June 2007	World Cup 2007, San Francisco, USA	Hansaram	KAIST, South Korea	37:30.00 (42.195 minutes)
25th July 2008	WorldCup 2008, Qingdao, China	aiRobot	National Cheng Kung University, Taiwan	04:35.00 (42.195 minutes)
20th July 2011	WorldCup 2011, Kaohsiung, Taiwan	Team Plymouth	Plymouth University, U.K.	07:35.00 (84.390 minutes)
27th Oct 2013	IRC Korea HuroCup	Kobots	Kookmin University	07:30.94 (120.00 minutes)

Table 3 The world record of HuroCup on junior-team weight lifting

Date	Event	Team	Affiliation	Time
7th August 2018	World Cup 2018, Taichung, Taiwan	Killer	Russia	104 Disks

weight lifting is broken by junior team for 104 disks, as shown in Table 3. This fact demonstrates that many research topics of humanoid robot cannot be explained and developed by only theories.

The ultimate objective of HuroCup is to develop humanoid robots to challenge human athletes. In FIRA 2018, the organizers held the archery competition of humanoid robots against human. This is the first time that humanoid robot challenged human athlete in the world. In this archery competition, the human teams are from Dode Elementary School and Chung Kung Senior High School, at Taichung. Both teams do constant training schedules in a professional archery club at Taichung. Many teammates are trained to become Olympic players by representing Taiwan.

Because the humanoid robot needs to do other event, not only archery, we also need to do much work on software for the archery competition. More specially, in this paper, the motion planning of both arms for more torque on bow and string is proposed.

This paper is organized as follows. In Section 2, the adult-sized humanoid is designed and implemented for the archery competition against human. In Section 3, the special work on the humanoid robot for archery is described. In Section 4, the archery competition between humanoid robot and human is described. Conclusions and further development are included in Section 5.

2 Design and implementation of a humanoid robot for HuroCup

In this section, design and implementation of a humanoid robot for HuroCup 10 events are proposed. Because powerful legs are the essential modules of humanoid robots for HuroCup on many events, such as sprint, lift and carry, and marathon. In this paper, a special steeling structure of joints for powerful legs is designed. Such special structure is designed to provide excellent basic capability of the humanoid robot for HuroCup.

Figure 1 shows the special steeling structure on one of the knee joints. In this special structure, the joint angle is steeled by iron chain whose both sides are terminated by two springs, respectively. In Figure 1, left photo shows the joint angle at normal position as the spring in releasing situation, and right photo shows the joint angle steeled by motor for pushing spring. The spring saves energy in pushing situation and releases energy as setting free. The energy saved in pushing spring is released to provide extra instantaneous torque by setting free. In addition to motor torque, such special steeling structure

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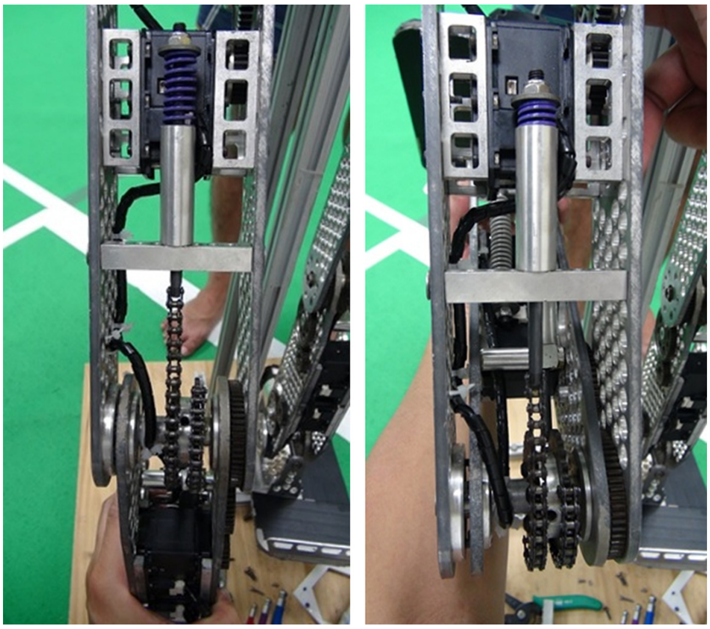

Figure 1 The special steeling structure of humanoid robot knee joints

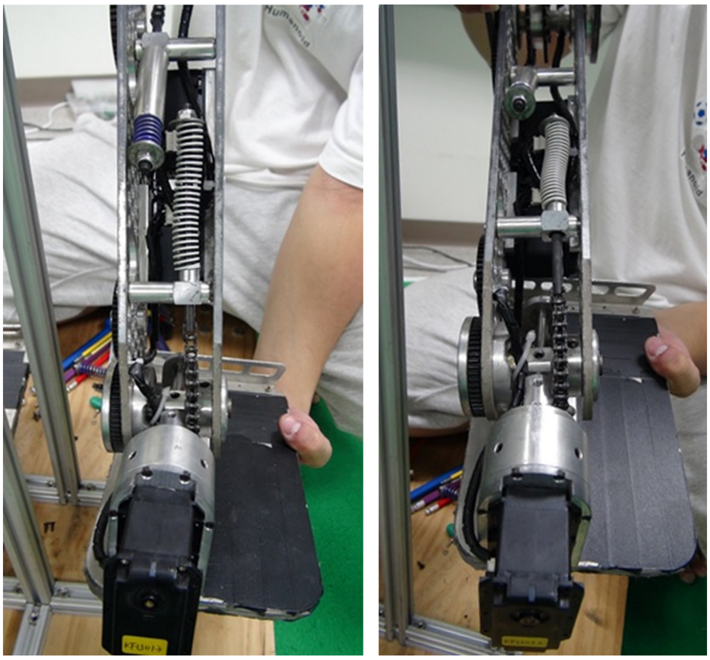

Figure 2 The steeling joint structure of humanoid robot ankle

provides extra instantaneous torque saved in the spring for motor rotation. Later, to demonstrate the capability of special steeling structure, a special experiment is designed and conducted. In addition to the special steeling structure of knee joint as shown in Figure 1 and that of ankle join is shown in Figure 2. In Figure 2, left photo is the spring in releasing situation, and right photo is the spring in pushing situation. Similarly, such special steeling structure provides extra torque for humanoid robot ankle via spring from pushing to releasing.

Figure 3 is the lower body of the humanoid robot and its kinematic model, where Z_i (for $i = 1, 2, \ldots,$ 14) are the Z-axes of all joints, and a_i are the distance between Z_{i-1} and Z_i. To evaluation its capability, 3.815 kg load put on the top of its lower body is experimented. For the experiment, the humanoid robot

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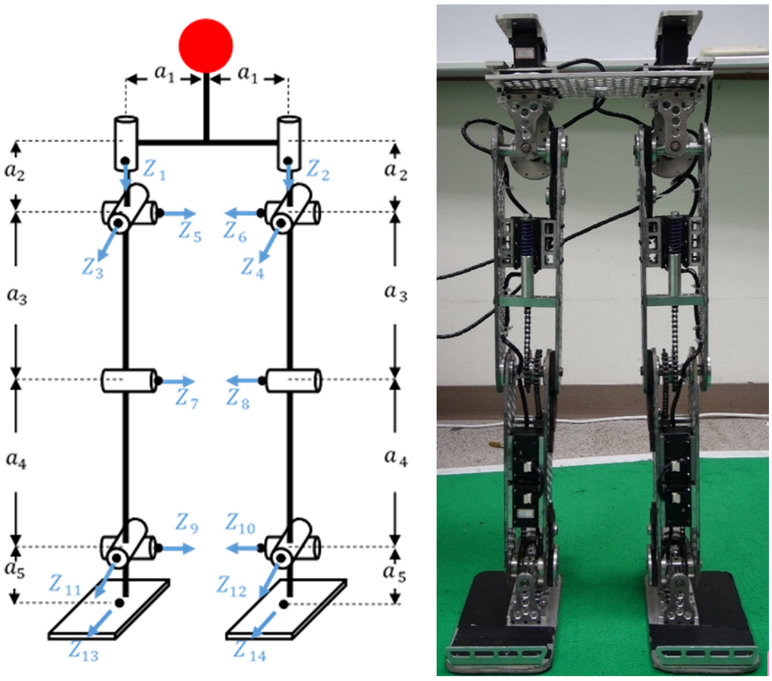

Figure 3 Both legs of the humanoid robot and its kinematic model

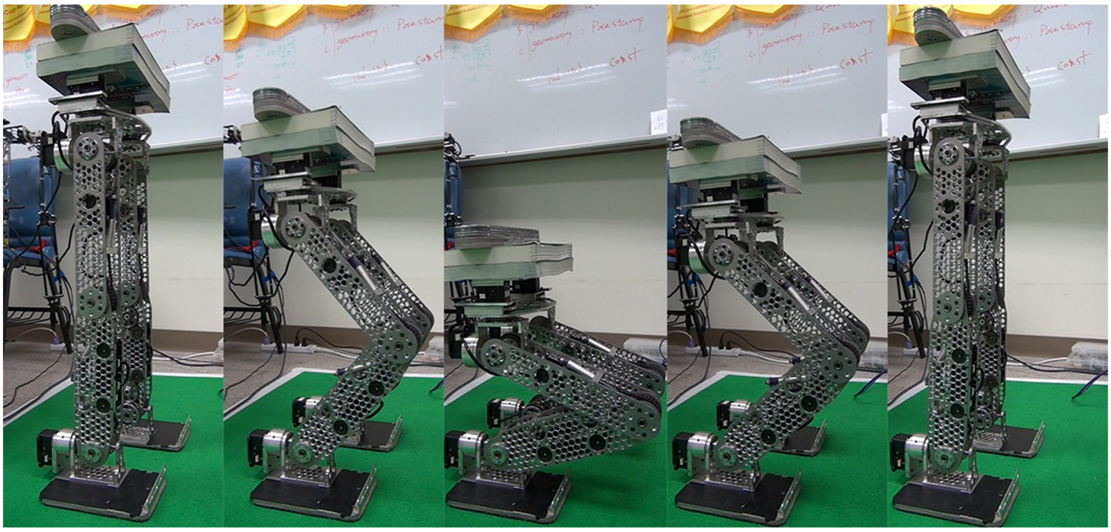

Figure 4 The humanoid robot does the posture from squat down to stand up as 3.815 kg load put on the top of its lower body

does the postures from squat down to stand up as shown in Figure 4. Figures 5 and 6 show the trajectories of knee joint position and torque, respectively. As shown in Figure 5, the position trajectories are completed when adding spring on the knee joints. On the upper part of Figure 5, the position trajectories are incomplete when no spring. Specially, the trajectories are in uncontrolled situation. Actually, the humanoid robot falls down. Figure 6 shows the torque trajectories. As shown in Figure 6, the torque trajectories are smaller when adding spring, and those ask too much torque more than motor output when no spring. This experiment result demonstrates that when adding spring on joints, the motors have enough torque to squat down and then stand up. Thus, the joint torque is under the limitation of motor output, and then the joint position follows desired trajectories.

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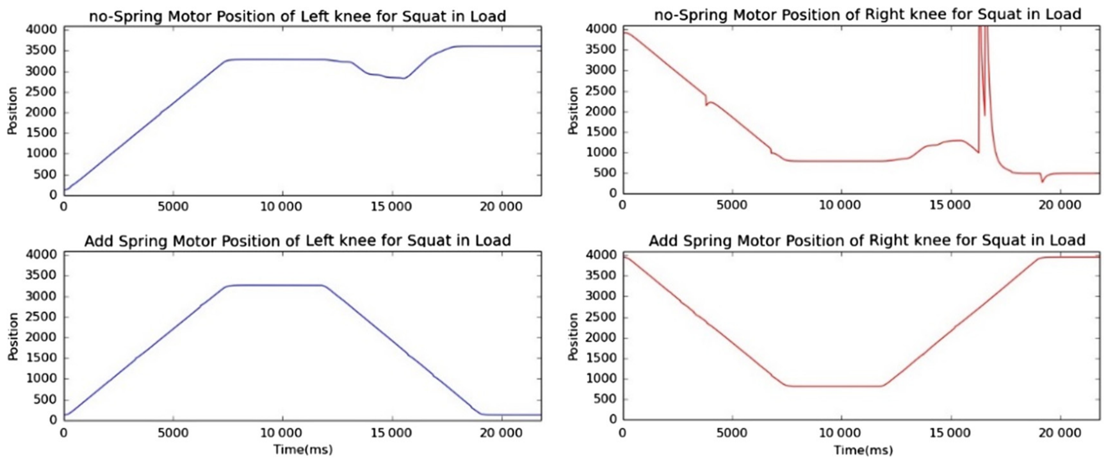

Figure 5 The compassion of no spring and adding spring when the humanoid robot squat down and then stand up as 3.815 kg load on its top of lower body. Left are the position trajectories of left knee joints and right are those of right knee joints

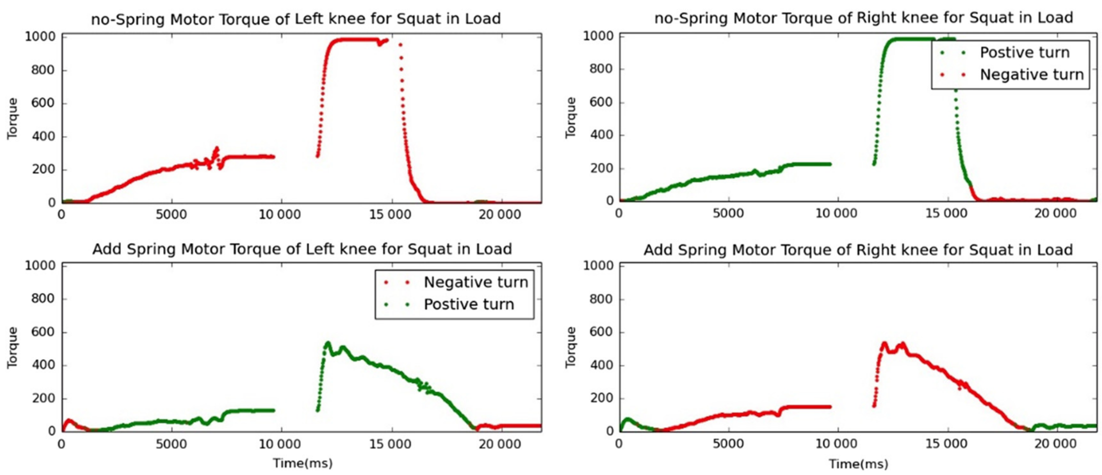

Figure 6 The compassion of no spring and adding spring when the humanoid robot squat down and then stand up as 3.815 kg load on its top of lower body. Left are the torque trajectories of left knee joints and right are those of right knee joints

Finally, the humanoid robot including upper body is designed and implemented for archery, as shown in Figure 7. The length of upper body is 450 mm, and the length of upper and lower arm is 225 and 180 mm, respectively. In addition, its left finger is designed to hold bow, and its right finger is designed to pull string. In the next section, the motion planning of both arms to have stronger force for shooting arrow is described.

From D-H rule (Craig, 2005), the homogenous transformation matrix between adjacent coordinate systems can be expressed by

$$^{n-1}T_n = \mathrm{Rot}_{X_{n-1}}(\alpha_{n-1}) \cdot \mathrm{Trans}_{X_{n-1}}(a_{n-1}) \cdot \mathrm{Rot}_{Z_n}(\theta_n) \cdot \mathrm{Trans}_{Z_n}(d_n) \quad (1)$$

where Rot is the rotation matrix, Trans is the translation matrix, and the parameters of the matrices are defined as follows:

θ_n (Joint angle): the angle of rotation from the X_{n-1} axis to the X_n axis about the Z_{n-1} axis.
d_n (Joint distance): the distance from the origin of the $(n-1)$ coordinate system to the intersection of the Z_{n-1} axis and the X_n axis along the Z_{n-1} axis.

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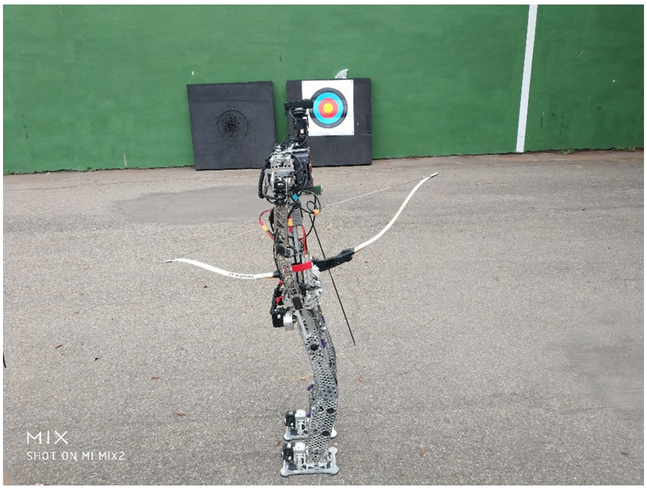

Figure 7 The humanoid robot designed for archery

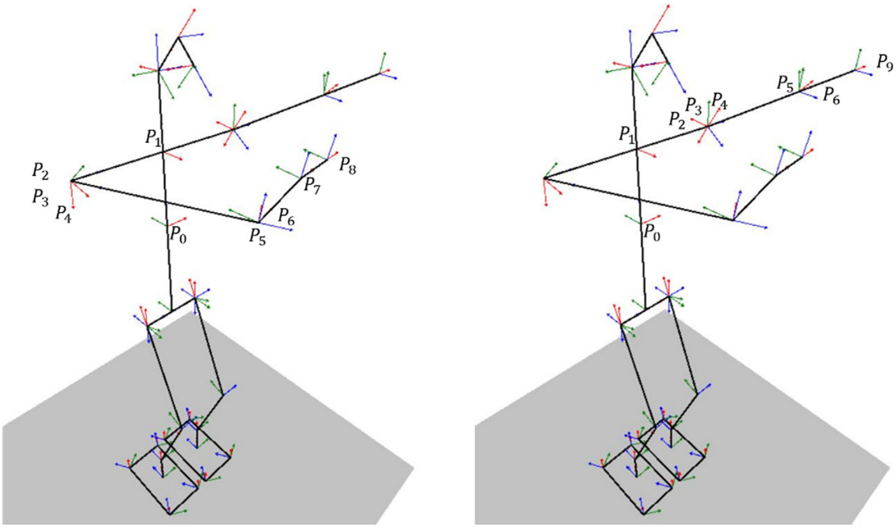

Figure 8 The forward kinematic models of right (left picture) and left (right picture) hands

a_{n-1} (Link length): the distance from the intersection of the Z_{n-1} axis and the X_n axis to the origin of the nth coordinate system along the X_n axis.

α_{n-1} (Link twist angle): the angle of rotation from the Z_{n-1} axis to the Z_n axis about the X_n axis.

Both hands of the humanoid robot are different fingers as shown in Figure 8. In Figure 8, left picture is the forward kinematic model of right hand and right picture is that of left hand. As shown in the left hand of Figure 8, right hand has fingers, P_7 and P_8, to pull bow string. But the left hand does not need fingers to pull the bow string and only needs to hold the bow. Therefore, the finger of left hand only has P_9 to hold bow, as shown in the right picture of Figure 8. The forward kinematics of both hands is represented by Table 4. Right finger has extra coordinate systems, P_7 and P_8, and left finger has extra coordinate system, P_9. This fact reflects in Table 5, and the forward kinematics of right and left hands is

$$\text{Right hand: } {}^0T_8 = {}^0T_1{}^1T_2{}^2T_3{}^3T_4{}^4T_5{}^5T_6{}^6T_7{}^7T_8, \text{ and} \tag{2}$$

$$\text{Left hand: } {}^0T_9 = {}^0T_1{}^1T_2{}^2T_3{}^3T_4{}^4T_5{}^5T_6{}^6T_9, \text{ respectively.} \tag{3}$$

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Table 4 The parameter table of both hands

I	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	a_0	−90
2	−90	0	$-a_1$	$\theta_2 + 90$
3	−90	0	0	$-90-\theta_4$
4	−90	0	0	θ_6
5	0	0	a_2	90
6	−90	0	0	$\theta_8 - 90$
7	0	a_3	0	θ_{10}
8	0	a_4	0	0
9*	0	$a_3 + a_5$	0	0

Table 5 The world record of HuroCup on kid-sized weight lifting

Date	Event	Team	Affiliation	Time
16th June 2007	WorldCup 2007, San Francisco, USA	Pie	Tamkung University, Taiwan	45 Disks
20th June 2008	EuroBy 2008, Linz, Austria	Pie	Tamkung University, Taiwan	46 Disks
23rd July 2008	WorldCup 2008, Qingdao, China	aiRobot	National Cheng Kung University, Taiwan	70 Disks
17th Sept. 2011	WorldCup 2011, Kaohsiung, Taiwan	Beyond	Nanyang Polytechnic, Singapore	80 Disks

Note that the parameters shown in Table 5 are $a_0 = 115$ mm, $a_1 = 140$ mm, $a_2 = 225$ mm, $a_3 = 130$ mm, $a_4 = 80$ mm, and $a_5 = 50$ mm, respectively. In the next section, the motion planning of holding the bow and shooting a string must apply the above forward kinematic equations.

3 Humanoid robot motion planning for archery

In addition to archery, the humanoid robot needs to play other nine events. The humanoid robot hardware including hands cannot be modified for only archery. In this section, the special motion planning of both hands of humanoid robot to produce much torque is proposed.

In the human–robot archery competition, the humanoid robot must engage professional bows. Usually, the professional bow is installed by strong string. In consideration of our humanoid robot hand torque, the archery bow with length 48 inches, weight 0.7 kg, and string 12 pounds (about 5.4 kg) is chosen for the competition. But, the motors of our humanoid robot hands cannot directly produce 12-pound torque to pull the bow's string. Thus, the motion planning of both hands to simultaneously pull the string is proposed.

The special motion planning of the archery shooting is separated into three postures: (1) prepare, (2) the beginning of pulling string, and (3) shooting. Prepare posture is the initial step to get ready for the start of shooting. At this posture, the humanoid robot takes the bow and arrow on lower position, as shown in Figure 9 (1). Because the bow weight is 0.7 kg and the torque to pull string is about 5.4 kg, in idea calculation, one motor of humanoid robot hands owns 6 Nm torque, and it can pull the string only 21.2 cm length. But, this bow size used by our humanoid must pull the string length to 500 cm. Therefore, the motor torque of the humanoid robot is not enough to take the bow up and to pull the string. Instead

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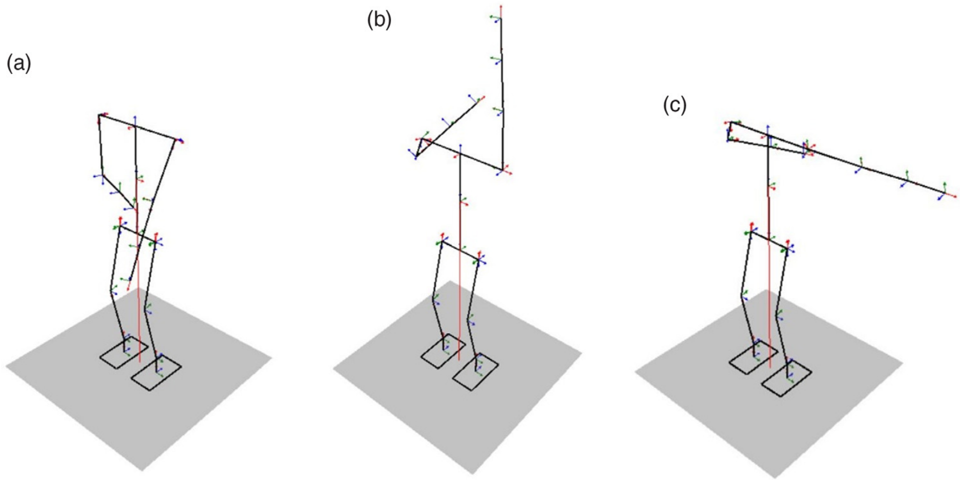

Figure 9 Three postures of the humanoid robot to play archery

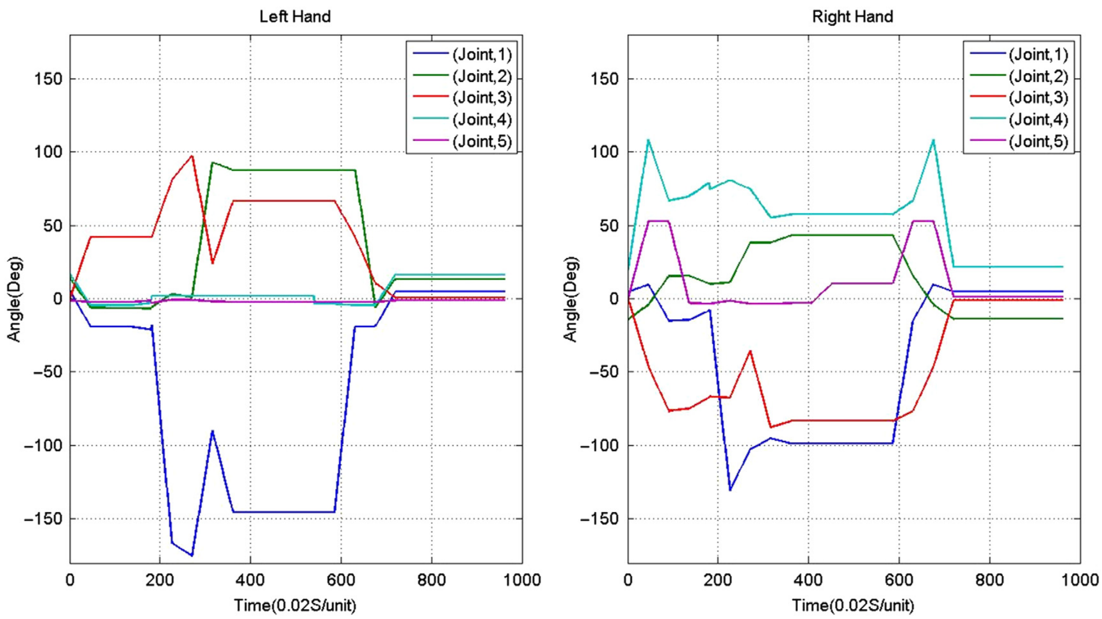

Figure 10 The time trajectories of joint angles planned for shooting procedure

of taking the bow up and pulling its string to avoid overcoming gravity, the humanoid robot goes into postures (2). Therefore, the shooting procedure going postures from (1) to (2) is to take the bow and arrow, not pulling string. Figure 9 (2) shows the humanoid robot on posture (2), the beginning of pulling string. Anyway, posture (2) for shooting is most difficult in the shooting procedure. The beginning of pulling string is the bow and arrow on the top of the humanoid robot body. The motion planning is the posture from postures (2) to (3). The motion planning from top to down to pull string simultaneously makes use of left and right hands to produce much torque. In this step, the benefit of pulling string from top to down can borrow the gravity of bow to produce much torque as well. The action of posture (3) is to move arrow to aim at the target center, as shown in Figure 9 (3). After planning the three postures, the time trajectories of all joints of both hands can be resulted from Equations (1) to (3). Figure 10 shows the time trajectories of all hand joints to complete the shooting procedure.

The shooting procedure is exactly implemented for our humanoid robot. During the shooting, three postures of the actual humanoid robot are shown in Figures 11–13, respectively.

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Figure 11 The archery shooting posture (1): prepare

Figure 12 The archery shooting posture (2): pulling string

Figure 13 The archery shooting posture (3): shooting

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4 Robot–humanoid archery challenge

The competition of human–robot archery challenge engages international Olympia rule. Under the rule, in every game, each team owns three arrows to count the shooting score. The team getting more shooting score wins the game and gets two points. The team that loses the game gets zero point. If both teams get the same score, both teams get one point, respectively. In a match, they play more games until one team gets six points. The team that first gets six points wins the match.

In the competition, Chung Kong Senior High School from human teams and NKUST from humanoid robot teams went to finalize the championship. In the championship competition, because of missing the humanoid robot calibration, NKUST lost the first two games. Therefore, Chung Kong Senior High School got points from the first two games. In the third game, NKUST got top 10 scores on the first two arrows and had same score with Chung Kong Senior High School. Unfortunately, NKUST missed camera tracking and only got 9 scores on the third arrow. Therefore, NKUST lost the third game too. Finally, Chung Kong Senior High School got championship, and NKUST only got second place.

Before the archery competition, we took our humanoid robots to visit Tiachung Archery Club for more archery shooting learning and practical. Our learning and practical are together with human teams, Dode Elementary School and Chung Kong Senior High School. The authors, Jacky Baltes and Kuo-Yang Tu went together to learn more about professional shooting skill. Then, we can know how to adjust and improve our humanoid robot archery shooting. We made the learning and practical archery shooting at Taichung club in video as shown in https://youtu.be/ernjVNQrj68.

5 Conclusions and further development

HuroCup is organized to develop full capability humanoid robots. From 2002 start, the capability of humanoid robot development is improved quickly. As shown in Table 1 for sprint, the humanoid robots can walk much quickly. As shown in Table 2 for marathon, the humanoid robots can walk longer. As shown in Table 5 for weight lifting, the humanoid robots can pick up heavier bar. Through the HuroCup competition, researchers are gathered to improve humanoid robot capability.

On FIRA 2018, a great challenge of human–robot archery competition is organized. Although human won the archery competition, it is a great step of humanoid robot research. In addition, the complex and redundant structure of humanoid robot is engaged to develop much torque of dual arm action based a sequent postures for archery shooting. We may conclude that similar to human, humanoid robots are possible to complete the challenge we cannot image.

It is not only the progress of humanoid robot research but also robot in human life. At present, humanoid robots can challenge the skills of human athletes. In the future, humanoid robots are possible to beat human athletes. To play with athletes, humanoid robots are very exciting and interactive with human. It is a good way to develop robots in human life under controllable safety. It brings us bright imagination on robotics for the industries of competition, entertainment, and so on. This research is inductive on the bright trend of robots in human life in the future.

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