XVII International Scientific Conference on Industrial Systems (IS'17)
Novi Sad, Serbia, October 4. – 6. 2017.
University of Novi Sad, Faculty of Technical Sciences,
Department for Industrial Engineering and Management
Available online at http://www.iim.ftn.uns.ac.rs/is17

Social Humanoid Robot SARA: Dynamic Analysis of the Arm

Marko Penčić
(Research Associate, University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia, e-mail: mpencic@uns.ac.rs)

Maja Čavić
(Associate Professor, University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia, e-mail: scomaja@uns.ac.rs)

Branislav Borovac
(Full Professor, University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia, e-mail: borovac@uns.ac.rs)

Milan Rackov
(Assistant Professor, University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia, e-mail: racmil@uns.ac.rs)

Abstract

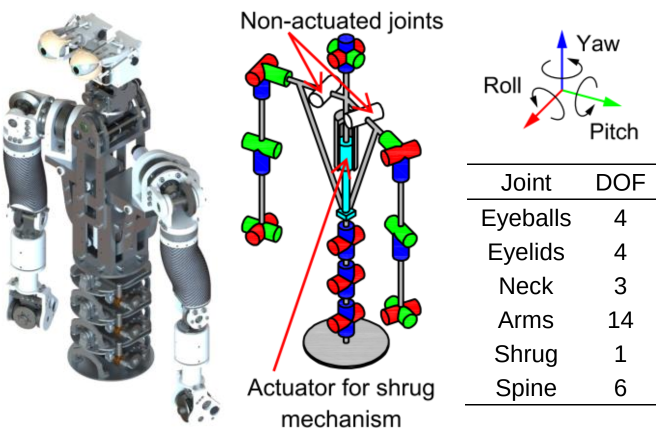
There are two basic ways for the mechanical realization of the arm of humanoids. The first is based on biologically inspired structures that have variable stiffness, and the second one on coaxial mechanisms that have high stiffness. We propose an anthropomorphic arm which is based on rigid and low backlash mechanisms. All joints are rotational and have 1 DOF. The paper presents a dynamic analysis of the arm with 7 DOFs for humanoid robots. The research was conducted within the project which develops the social humanoid robot Sara. Based on the set kinematics and dynamic requirements, a dynamic model of the arm was formed, a dynamic simulation was performed and driving torques in the joints were determined. The analysis is performed depending on the type of movement and the range of arm motion. Three characteristic movements were simulated for each joint. Maximal driving torques are identified in first two shoulder joints during flexion and abduction of the arm. Driving torques for upper arm rotation and elbow flexion have approximately four times less value.

Key words: *driving torque, dynamic analysis, humanoid, robot arm*

1. INTRODUCTION

Human arm is one of the most important limbs because it performs the complex actions of grasping and manipulating objects in space. The same versatility is required from humanoid robots, and, given the mobility of the human arm, very serious technical requirements are imposed for the humanoid arm design. Since the robot is expected to be able to perform manipulation tasks of the approximately same complexity as a human, we decided to create an arm that has the same number of degrees of freedom as the human arm, with the hand excluded.

The paper presents a dynamic analysis of the arm for humanoid robots. The research was conducted within the project which develops the humanoid robot Sara – an anthropomorphic mobile platform for the research of social behaviour of robots. Sara will be able to communicate verbally and nonverbally. To express facial expressions, biologically inspired eyes and eyelids with 8 DOFs are being developed [1]. In order to extend the spectrum of nonverbal communication, the robot will be able to shrug when the answer is confusing and when it does not know what to answer [2]. In addition, Sara will have two anthropomorphic arms with 14 DOFs, a self-locking and low backlash neck mechanism with 3 DOFs [3] and a self-locking multi-segment lumbar spine with 7 DOFs [4] to increase the mobility of the robot upper body without moving the lower body.



Joint	DOF
Eyeballs	4
Eyelids	4
Neck	3
Arms	14
Shrug	1
Spine	6

Figure 1. Social humanoid robot SARA – current prototype and its kinematic structure

1.1 Human arm and its mobility

The arm is the most versatile part of the human body and it consists of the shoulder, upper arm, elbow, forearm, wrist and hand. Mobility is different for arm joints.

There are four groups of movements at the shoulder joint: flexion, extension and hyperextension – Fig. 2(a-c), abduction and adduction – Fig. 2(d-e), lateral and medial rotation – Fig. 2(f-g), and horizontal abduction and adduction – Fig. 2(h-i). Movements of flexion, extension and hyperextension occur in the sagittal plane – lateral, around the pitch axis. Flexion is from 0 to 180° and extension is the return to the anatomical position. There are approximately 45° of hyperextension from anatomical position. Movements of abduction and adduction occur in the frontal plane around the roll axis with 180° of motion possible. Movements of medial and lateral rotation occur in the transverse plane around the pitch axis. Sometimes the terms internal and external are used in place of medial and lateral, respectively. From a neutral position, it is possible to move 90° in each direction. Movements of horizontal abduction and adduction also occur in the transverse plane around the yaw axis. The starting position for these motions is at 90° of shoulder abduction. There are approximately 30° of horizontal abduction – backward motion, and approximately 120° of horizontal adduction. Circumduction is a term used to describe the arc or circle of movements at the shoulder joint – combination of all the shoulder movements.

The elbow is a uniaxial hinge joint that enables only movements of flexion and extension – Fig. 2(j-k). There are approximately 145° of flexion measured from the 0° position of extension. There is no active hyperextension at the elbow as there is at the shoulder joint. The articulation between the radius and ulna is known as the radioulnar joint. They articulate with each other at both ends. The radioulnar joint is a uniaxial pivot joint allowing only pronation and supination movements of the forearm – Fig. 2(l-m). Measured from the neutral or midposition, there are approximately 90° of supination and 80° of pronation.

The wrist joint is one of the most complex joints of the body. It is actually made up of two joints: the radiocarpal joint and the midcarpal joint. The radiocarpal joint is classified as a biaxial joint allowing movements of flexion and extension – Fig. 2(n-o), and movements of radial and ulnar deviation – Fig. 2(p-q). The midcarpal joint occur between the two rows of carpal bones and contribute to wrist motion. Their shape is irregular and they are classified as plane joint. They are nonaxial joints that allow gliding motions, which collectively contribute to radiocarpal joint motion. The combination of all four of these motions is called circumduction. There is no rotation at the wrist. Flexion and extension occur in the sagittal plane around the pitch axis. There are approximately 90° of flexion and 70° of extension. Movements in the direction of ulnar and radial deviation occur in the frontal plane around the roll axis. There are approximately 25° of radial deviation and 35° of ulnar deviation [5].

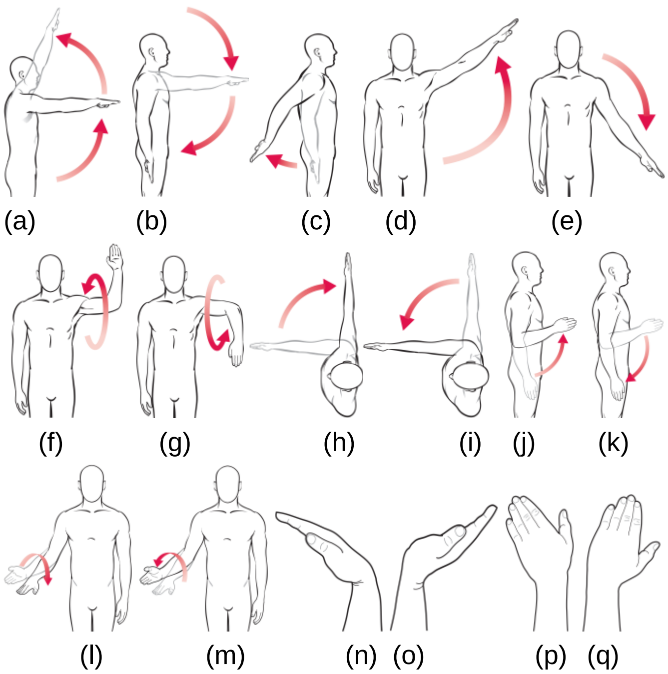


Figure 2. Movements of the arm: (a)-(c) flexion, extension and hyperextension, (d)-(e) abduction and adduction, (f)-(g) lateral and medial rotation, (h)-(i) horizontal abduction and adduction, (j)-(k) elbow – flexion and extension, (l)-(m) forearm – pronation and supination, (n)-(o) wrist – flexion and extension, and (p)-(q) wrist – ulnar and radial deviation

2. STATE OF THE ART

There are two basic groups of robots that are able to move arms. The first group of robots has arms with 6 or 7 DOFs per arm where each joint has 1 DOF – rigid structures, while the second group of robots has arms with 9-13 DOFs per arm whereby joints have 1, 2 or 3 DOFs – flexible structure.

Robots with 6 DOFs arm are Infanoid [6], Pepper [7], Ever-1 [8], EveR-2 [9], Ever-3 [10], EveR-4M [11], Albert HUBO [12], TORO [13], KIBO [14], HUBO [15], HRP-4C [16] etc, while robots with 7 DOFs arm are iCub [17], Justin [18], James [19], Romeo [20], Robonaut 2 [21], CB [22], HRP-4 [23], BERT2 [24], KOBIAN [25], WABIAN-2 [26], ARMAR-III [27], AILA [28] etc. The arms of these robots consist of rigid and low backlash mechanisms that are interconnected – harmonic drives, cable-driven mechanisms, belt-driven mechanisms, spindle drives, low backlash gears etc. Beside high carrying capacity and reliability, these mechanisms have low backlash that provides high positioning accuracy that enables high accuracy and repeatability of movements, which is essential for motion control.

Arms with 9-13 DOFs per arm are found in Kenta [29], Kenji [30], Kotaro [31], Kojiro [32], Kenzoh [33], Kenshiro [34] and Kengoro [35]. The mechanical structure of these robot arms mimics the human skeleton of artificial muscles that are based on NST – nonlinear spring units. NST have a nonlinear relationship between tension and spring constant of the tendon, and therefore the arms have variable stiffness. The advantage of NST is simple realization and implementation using only one spring and guided pulleys of tendon – wire.

3. DYNAMICAL ANALYSIS

There are two basic problems that occur in robot arm realization – large masses of the segments and the backlash in joints which is essential for motion control. In order to minimize driving torques in the arm joints, it is necessary to minimize the mass of the segments as well as to move their centres of mass as close as possible to the shoulder joint. Therefore, shoulder actuators should be positioned in the joint itself. In this way, their mass will be supported by the stationary basic segment. All other actuators should be placed close to the shoulder joint. The prototype of SARA's arm has 7 DOFs: 3 DOFs shoulder, 2 DOFs elbow and 2 DOFs wrist – Fig. 1. Beside the harmonic drive which is used for upper arm rotation, all other reducers are based on low backlash helical and bevel gears.

Arm movements have to look natural so their average duration is set to be 1 s – at the beginning as well as at the end of the movement, arm is in a standstill. At this phase of the development, the hand is approximated as a prismatic rigid body with the mass of 1 kg. Fig. 3 shows the kinematical configuration of the arm which has seven segments and the first one is basic – geometric and dynamic parameters are given in Tables 1 and 2. The dynamical model was formed based on the CAD model of the arm, a simulation was performed and the driving torques in the robot arm joint were calculated. Three different movements, considering movement type and amplitude, were simulated for each joint, Figs. 4 – 8. Time histories of the driving torques are presented in Figs. 9 and 10. Maximal values of the driving torques are given in Table 3. Simulation was performed in the software that forms a dynamic model of a multibody system [36]. The modelling is based on the concept of a free-flying mechanism, which consists of one or more kinematic chains whose links are interconnected by revolute joints with 1 degree of freedom. Law motions were prescribed for each joint – displacement is defined by a third degree polynomial.

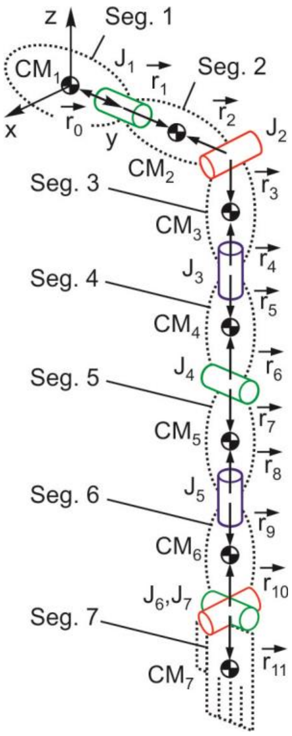


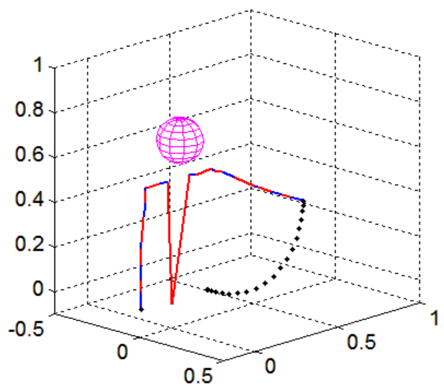
Figure 3. Kinematic configuration

Table 1. Geometric parameters

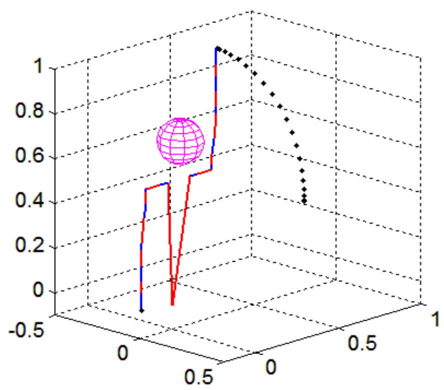
Vector	Coordinates x [mm]	y [mm]	z [mm]
r_0	–40.35	0	–78.70
r_1	–8.14	37.58	–2.16
r_2	–8.14	–91.95	–2.16
r_3	–4.31	0	–19.4
r_4	–4.31	0	50.1
r_5	–12.35	0	–68.05
r_6	13.65	0	115.94
r_7	0	2.85	–28.16
r_8	0	2.85	71.34
r_9	–3.38	0	–70.38
r_{10}	–3.38	0	50.12
r_{11}	0	0	–75

Table 2. Dynamic parameters

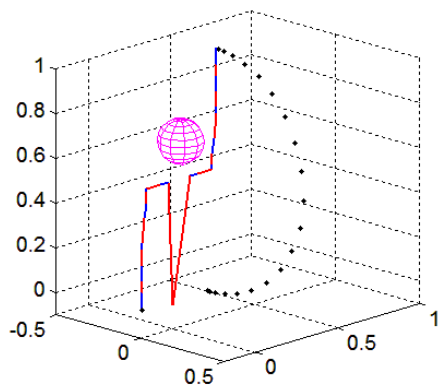
Segment	Mass [kg]	Centre of mass x [mm]	y [mm]	z [mm]	Moments of inertia I_{xx} [kgmm^2]	I_{yy} [kgmm^2]	I_{zz} [kgmm^2]
1	0.884	0	0	0	3115.68	2965.39	1120.38
2	1.254	32.21	37.58	76.54	2020.48	913.67	2468.94
3	0.628	36.04	129.53	59.29	528.04	559.79	337.63
4	0.894	27.99	129.60	–58.86	3819.06	3949.03	568.23
5	0.362	14.35	132.38	–202.96	420.39	400.97	142.52
6	0.881	10.97	129.53	–344.68	3269.46	3115.71	480.57
7	1	14.35	129.53	–469.81	2550.24	1908.35	708.58



(a)



(b)



(c)

Figure 4. Dynamical simulation (joint J_1): arm flexion for the range of motion (a) 0÷90°, (b) 90÷180° and (c) 0÷180°

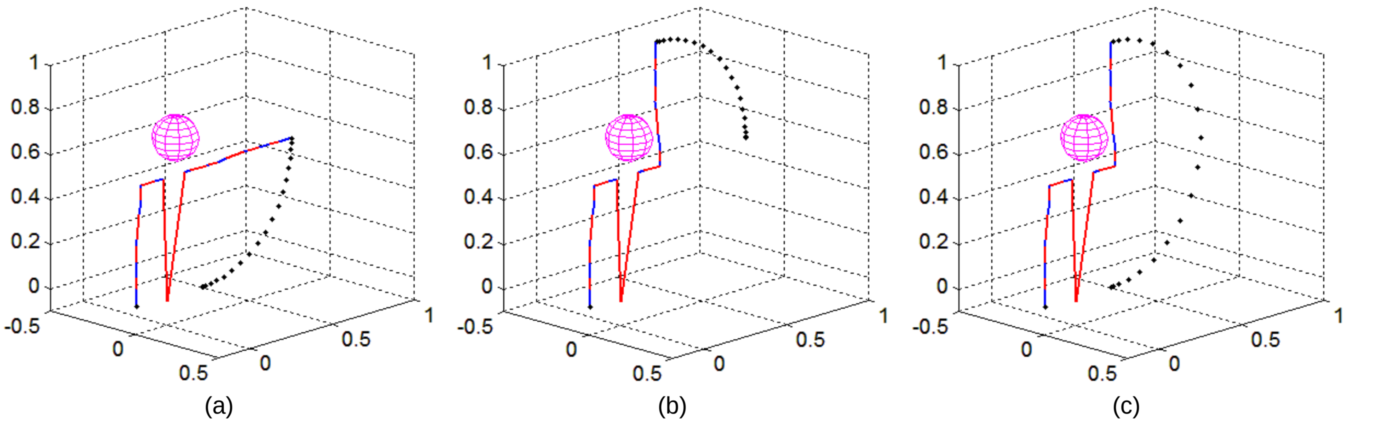


Figure 5. Dynamical simulation (joint J_2): arm abduction for the range of motion (a) 0÷90°, (b) 90÷180° and (c) 0÷180°

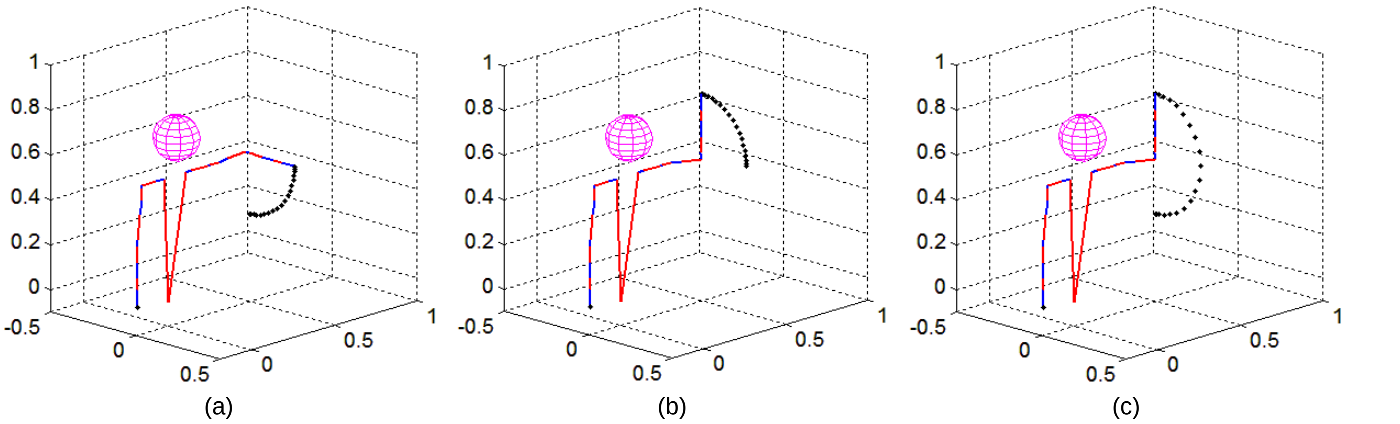


Figure 6. Dynamical simulation (joint J_3): arm lateral rotation for the range of motion (a) 0÷90°, (b) 90÷180° and (c) 0÷180°

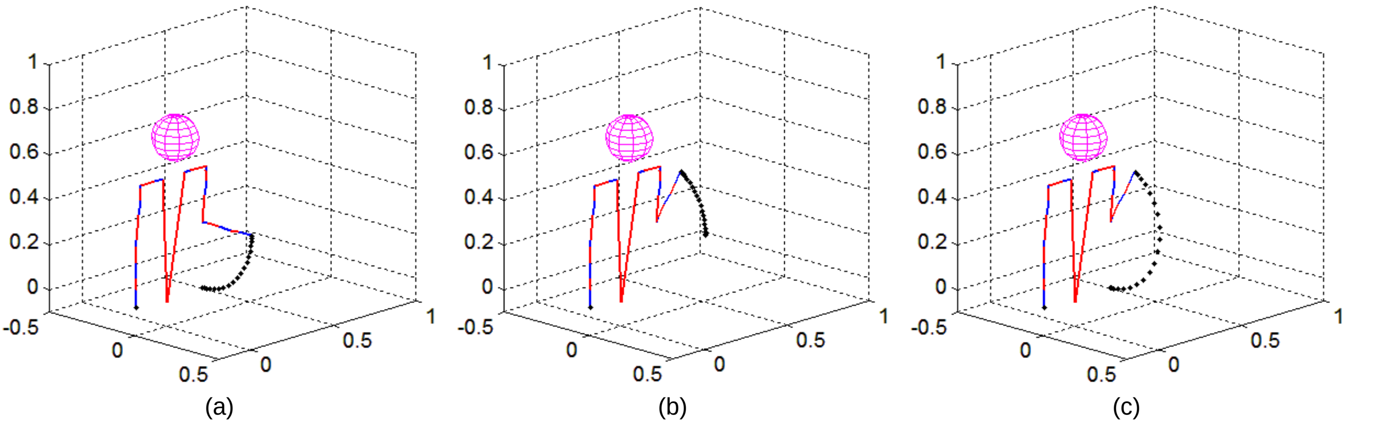


Figure 7. Dynamical simulation (joint J_4): elbow flexion for the range of motion (a) 0÷90°, (b) 90÷150° and (c) 0÷150°

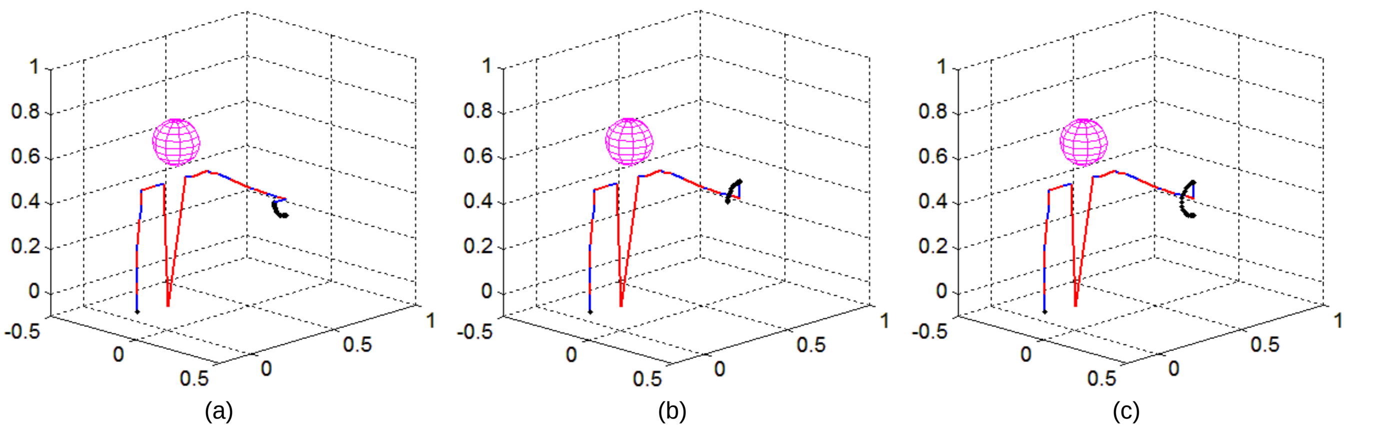


Figure 8. Dynamical simulation (joint J_5): forearm supination for the range of motion (a) 0÷90°, (b) 90÷180° and (c) 0÷180°

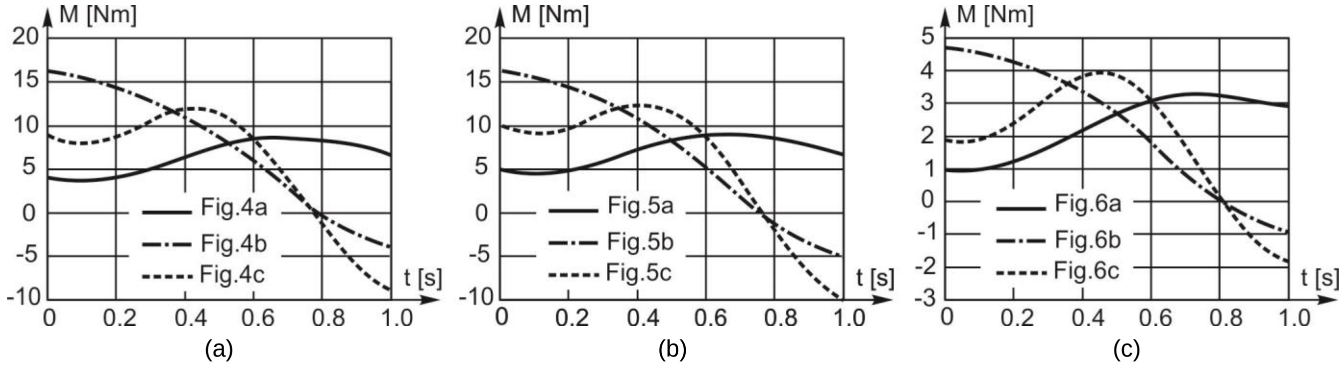


Figure 9. Time histories of the driving torques in: (a) joint J_1, (b) joint J_2 and (c) joint J_3

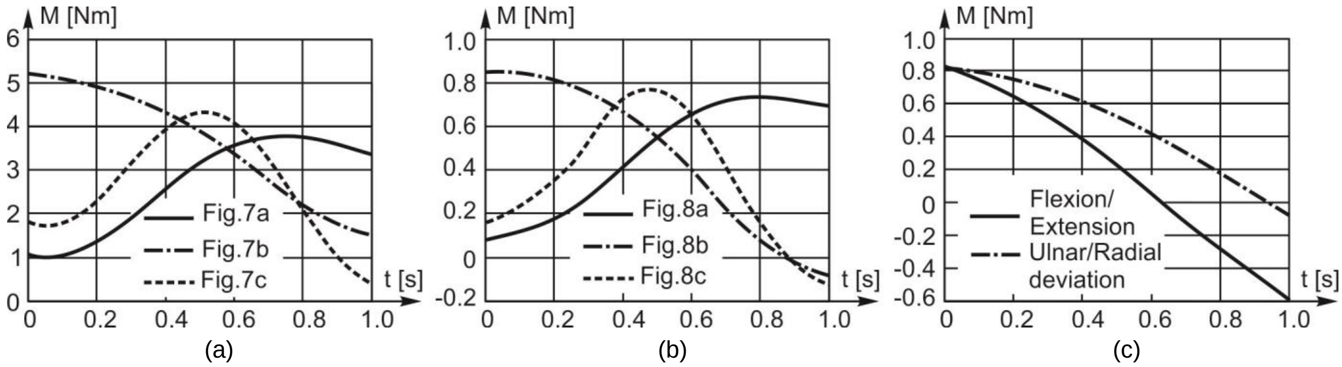


Figure 10. Time histories of the driving torques in: (a) joint J_4, (b) joint J_5 and (c) wrist joint J_6,J_7

Table 3. Simulation results – maximum driving torques in joints

Joint	Shoulder (J_1)	Shoulder (J_2)	Shoulder (J_3)	Elbow (J_4)	Forearm (J_5)	Wrist (J_6)	Wrist (J_7)
Movement	Flexion	Abduction	Lateral rotation	Flexion	Supination	Flexion/Extension	Ulnar/Radial deviation
Torque [Nm]	16.26	16.21	4.69	4.31	0.76	0.83	0.81

5. CONCLUSION

Dynamic analysis of the humanoid robot arm with 7 DOFs is presented in this paper. The arm has 3 DOFs shoulder, 2 DOF elbow and 2 DOFs wrist – all joints are rotational and have 1 DOF. In order to minimize driving torques, shoulder actuators are placed inside the shoulder joint itself, while all other actuators are positioned as high as possible, i.e. close to the shoulder and elbow joint. To form the dynamical model, the humanoid arm was divided into seven segments interconnected with 1 DOF rotational joints, whereby first segment is basic and immovable. Based on the set kinematics and dynamic requirements, a dynamic model of the arm was formed, a dynamic simulation was performed and driving torques in the joints were determined. Three characteristic movements were simulated for each joint – movement type and range of motion were changed. Maximal driving torques are identified in the first two shoulder joints during flexion and abduction of the arm. Driving torques for upper arm rotation and elbow flexion have approximately four times less value. Composite movements and their influence on the arm dynamics will be investigated in the further work.

6. ACKNOWLEDGMENT

This work was funded by the Ministry of Education and Science of the Republic of Serbia under the contract III44008 and by the Provincial Secretariat for Science and Technological Development under the contract 114–451–2116/2011.

7. REFERENCES

[1] Penčić, M., Čavić, M., Rackov, M., Borovac, B. and Lu, Z. (2017), "*Drive System of the Robot Eyeballs and Eyelids with 8 DOFs*", Proceedings of the 12th IFToMM International Symposium on Science of Mechanisms and Machines – SYROM, Iasi, Romania, to be published.

[2] Penčić, M., Čavić, M. and Borovac, B. (2017), "*Optimal Synthesis of the Worm-Lever Mechanism for Humanoid Robots Shrug*", Serbian Journal of Electrical Engineering, Vol. 14, No. 2, pp. 245–256.

[3] Penčić, M., Čavić, M. and Borovac, B. (2016), "*Analysis of Mechanisms for Achieving Different Ways of Power Transmission and Motion of the Anthropomorphic Robots Upper Body*", Proceedings of the 5th International Conference on Power Transmission – BAPT, Ohrid, Macedonia, pp. 115–122.

[4] Penčić, M., Borovac, B., Kovačević, D. and Čavić, M. (2016), "*Development of the Multi-Segment Lumbar Spine for Humanoid Robots*", Thermal Science, Vol. 20, Suppl. 2, pp. S581–S590.

[5] Lippert, S.L. (2006), *Clinical Kinesiology and Anatomy, F.A. Davis Company*, Philadelphia, PA, USA.

[6] Kozima, H. (2002), "*Infanoid, A Babybot that Explores the Social Environment*", In book: Dautenhahn, K., Bond, A., Cañamero, L. and Edmonds B. (Eds.) Socially Intelligent Agents: CRCR. MSASSO, Vol. 3, pp. 157–164, Springer.

[7] Lafaye, J., Gouaillier, D. and Wieber P.B. (2014), "*Linear Model Predictive Control of the Locomotion of Pepper, a Humanoid Robot with Omnidirectional Wheels*", Proceedings of the 14th IEEE-RAS International Conference on Humanoid Robots – Humanoids, Madrid, Spain, pp. 336–341.

[8] Ahn, H.S., Lee, D.-W., Choi, D., Lee, D.-Y., Lee, H.-G. and Baeg M.-H. (2013), "*Development of an Incarnate Announcing Robot System Using Emotional Interaction with Humans*", International Journal of Humanoid Robotics, Vol. 10, No. 2, pp. 1350017-1–1350017-24.

[9] Ahn, H.S., Lee, D.-W., Choi, D., Lee, D.Y., Hur, M.H., Lee, H. and Shon, W.H. (2011), "*Development of an Android for Singing with Facial Expression*" Proceedings of the 37th Annual Conference of the IEEE Industrial Electronics Society – IECON, Melbourne, Australia, pp. 104–109.

[10] Ahn, H.S., Lee, D.-W., Choi, D., Lee, D.-Y., Hur, M. and Lee, H. (2013), "*Actor Studio: Development of User Friendly Action Editing System for Cultural Performance Robots*", In book: Lee, S., Cho, H., Yoon, K.-J. and Lee, J. (Eds.) Intelligent Autonomous Systems: IAS-12. AISC, Vol. 193, pp. 447–455, Springer.

[11] Ahn, H.S., Lee, D.-W., Choi, D., Lee, D.-Y., Hur, M. and Lee, H. (2012), "*Uses of Facial Expressions of Android Head System according to Gender and Age*", Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics – SMC, Seoul, South Korea, pp. 2300–2305.

[12] Park, I.-W., Kim, J.-Y., Cho, B.-K. and Oh, J.-H. (2008), "*Control Hardware Integration of a Biped Humanoid Robot with an Android Head*", Robotics and Autonomous Systems, Vol. 56, No. 1, pp. 95–103.

[13] Englsberger, J., Werner, A., Ott, C., Henze, B., Roa, M.A., Garofalo, G., Burger, R., Beyer, A., Eiberger, O., Schmid, K. and Albu-Schäffer, A. (2014) "*Overview of the Torque-Controlled Humanoid Robot TORO*", Proceedings of the 14th IEEE-RAS International Conference on Humanoid Robots – Humanoids, Madrid, Spain, pp. 916–923.

[14] Lee, S., Kim, J.-Y. and Kim, M. (2013),"*Development and Walking Control of Emotional Humanoid Robot, KIBO*", International Journal of Humanoid Robotics, Vol. 10, No. 4, pp. 1350024-1–1350024-35.

[15] Park, I.-W., Kim, J.-Y., Lee, J. and Oh, J.-H. (2007), "*Mechanical Design of the Humanoid Robot Platform, HUBO*", Advanced Robotics, Vol. 21, No. 11, pp. 1305–1322.

[16] Kajita, S., Kaneko, K., Kaneiro, F., Harada, K., Morisawa, M., Nakaoka, S., Miura, K., Fujiwara, K., Neo, E.S., Hara, I., Yokoi, K. and Hirukawa, H. (2011), "*Cybernetic Human HRP-4C: A Humanoid Robot with Human-Like Proportions*", In book: Pradalier, C., Siegwart, R. and Hirzinger G. (Eds.) Robotics Research: 14th ISRR. STAR, Vol. 70, pp. 301–314, Springer.

[17] Tsagarakis, N.G., Metta, G., Sandini, G., Vernon, D., Beira, R., Becchi, F., Righetti, L., Santos-Victor, J. Ijspeert, A.J., Carrozza, M.C. and Caldwell D.G. (2007), "*iCub: the Design and Realization of an Open Humanoid Platform for Cognitive and Neuroscience Research*" Advanced Robotics, Vol. 21, no. 10, pp. 1151–1175.

[18] Ott, C., Eiberger, O., Friedl, W., Bauml, B., Hillenbrand, U., Borst, C., Albu-Schaffer, A., Brunner, B., Hirschmuller, H., Kielhofer, S., Konietschke, R., Suppa, M., Wimbock, T., Zacharias, F. and Hirzinger, G. (2006), "A Humanoid Two-Arm System for Dexterous Manipulation", Proceedings of the 6th IEEE-RAS International Conference on Humanoid Robots – Humanoids, Osaka, Japan, pp. 276–283.

[19] Jamone, L., Metta, G., Nori, F. and Sandini, G. (2006), "*James: A Humanoid Robot Acting over an Unstructured World*", Proceedings of the 6th IEEE-RAS International Conference on Humanoid Robots – Humanoids, Genova, Italy, pp. 143–150.

[20] Claudio, G., Spindler, F. and Chaumette, F. (2016), "Vision-based Manipulation with the Humanoid Robot Romeo", Proceedings of the 16th IEEE-RAS International Conference on Humanoid Robots – Humanoids, Cancun, Mexico, pp. 286–293.

[21] Diftler, M.A., Mehling, J.S., Abdallah, M.E., Radford, N.A., Bridgwater, L.B., Sanders, A.M., Askew, R.S., Linn, D.M., Yamokoski, J.D., Permenter, F.A., Hargrave, B.K. and Platt, R. (2011), "*Robonaut 2 – The First Humanoid Robot in Space*", Proceedings of the IEEE International Conference on Robotics and Automation – ICRA, Shanghai, China, pp. 2178–2183.

[22] Cheng, G., Hyon, S.-H., Morimoto, J., Ude, A., Hale, J.G., Colvin, G., Scroggin, W. and Jacobsen, S.C. (2007), "*CB: a Humanoid Research Platform for Exploring Neuroscience*", Advanced Robotics, Vol. 21, No. 10, pp. 1097–1114.

[23] Kaneko, K., Kanehiro, F., Morisawa, M., Akachi, K., Miyamori, G., Hayashi, A. and Kanehira, N. (2011), "*Humanoid robot HRP-4 – Humanoid Robotics Platform with Lightweight and Slim Body*", Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems – IROS, San Francisco, CA, USA, pp. 4400–4407.

[24] Lenz, A., Skachek, S., Hamann, K., Steinwender, J., Pipe, A.G. and Melhuish, C. (2010), "*The BERT2 Infrastructure: An Integrated System for the Study of Human-Robot Interaction*", Proceedings of the IEEE-RAS International Conference on Humanoid Robots – Humanoids, Nashville, TN, USA, pp. 346–351.

[25] Zecca, M., Endo, N., Momoki, S., Itoh, K. and Takanishi, A. (2008), "*Design of the Humanoid Robot KOBIAN – Preliminary Analysis of Facial and Whole Body Emotion Expression Capabilities* –", Proceedings of the 8th IEEE-RAS International Conference on Humanoid Robots – Humanoids, Daejeon, South Korea, pp. 487–492.

[26] Ogura, Y., Aikawa, H., Shimomura, K., Kondo, H., Morishima, A., Lim, H.-O. and Takanishi A. (2006), "*Development of a New Humanoid Robot WABIAN-2**", Proceedings of the IEEE International Conference on Robotics and Automation – ICRA, Orlando, FL, USA, pp. 76–81.

[27] Albers, A., Brudniok, S., Ottnad, J. Sauter, C. and Sedchaicharn, K. (2006), "*Upper Body of a new Humanoid Robot – the Design of ARMAR III*", Proceedings of the 6th IEEE-RAS International Conference on Humanoid Robots – Humanoids, Genova, Italy, pp. 308–313.

[28] Lemburg, J., de Gea Fernández, J., Eich, M., Mronga, D., Kampmann, P., Vogt, A., Aggarwal, A., Shi, Y. and Kirchner, F. (2011), "*AILA – Design of an Autonomous Mobile Dual-Arm Robot* Proceedings of the IEEE International Conference on Robotics and Automation – ICRA, Shanghai, China, pp. 5147–5153.

[29] Inaba, M., Mizuuchi, I., Tajima, R., Yoshikai, T., Sato, D., Nagashi-ma, K. and Inoue, H. (2003), "*Building Spined Muscle-Tendon Humanoid*", In book: Jarvis, R.A. and Zelinsky, A. (Eds.) Robotics Research: 9th ISRR. STAR, Vol. 6, pp. 113–127, Springer.

[30] Mizuuchi, I., Yoshikai, T., Nakanishi, Y. and Inaba, M. (2005), "*A Reinforceable-Muscle Flexible-Spine Humanoid "Kenji"*," Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems – IROS, Edmonton, Canada, pp. 4143–4148.

[31] Mizuuchi, I., Yoshikai, T., Sodeyama, Y., Nakanishi, Y., Miyadera, A., Yamamoto, T., Niemela, T., Hayashi, M., Urata, J., Namiki, Y., Nishino, T. and Inaba, M. (2006), "*Development of Musculoskeletal Humanoid Kotaro*", Proceedings of the IEEE International Conference on Robotics and Automation – ICRA, Orlando, FL, USA, pp. 82–87.

[32] Mizuuchi, I., Nakanishi, Y., Sodeyama, Y., Namiki, Y., Nishino, T., Muramatsu, N., Urata, J., Hongo, K., Yoshikai, T. and Inaba, M. (2007), "*An Advanced Musculoskeletal Humanoid Kojiro*", Proceedings of the 7th IEEE-RAS International Conference on Humanoid Robots – Humanoids, Pittsburgh, PA, USA, pp. 294–299

[33] Izawa, T., Osada, M., Ito, N., Ohta, S., Urata, J. and Inaba, M. (2011), "*Development of Musculoskeletal Humanoid Kenzoh with Mechanical Compliance Changeable Tendons by Nonlinear Spring Unit*", Proceedings of the IEEE International Conference on Robotics and Biomimetics – ROBIO, Phuket, Thailand, pp. 2384–2389.

[34] Asano, Y., Kozuki, T., Mizoguchi, H., Motegi, Y., Osada, M., Shirai, T., Urata, J., Okada, K. and Inaba, M. (2012), "*Design Concept of Detail Musculoskeletal Humanoid Kenshiro – Toward a Real Human Body Musculoskeletal Simulator*", Proceedings of the 12th IEEE-RAS International Conference on Humanoid Robots – Humanoids, Osaka, Japan, pp. 811–816.

[35] Asano, Y., Kozuki, T., Ookubo, S., Kawamura, M., Nakashima, S., Katayama, T., Yanokura, I., Hirose, T., Kawaharazuka, K., Makino, S., Kakiuchi, Y., Okada, K. and Inaba, M. (2016), "*Human Mimetic Musculoskeletal Humanoid Kengoro toward Real World Physically Interactive Actions*", Proceedings of the 16th IEEE-RAS International Conference on Humanoid Robots – Humanoids, Cancun, Mexico, pp. 876–883.

[36] Vukobratović, M., Potkonjak, V., Babković, K. and Borovac, B. (2007). "*Simulation Model of General Human and Humanoid Motion*", Multibody System Dynamics, Vol. 17, No. 1, pp. 71–96.