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Teaching Basics of Serial Robot Chains's Kinematics to Computer Science Students

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Abstract - Understanding the geometry, kinematics and dynamics of serial robot chains using for computer science students is very challenging task. Therefore, adopting the corresponding methodology for teaching robotics in the undergraduate program is very important. Main goal of this paper is to validate the adopted approach to teach the kinematics of serial robot chains using virtual environments and physical humanoid robot. Moreover, the concept of visual programming of serial robotics chains vs. classical programming has also been evaluated.

I. Introduction

Technological advancements in the last couple of decades have contributed to robots' penetration in multiple sectors and have made them affordable and applicable even for personal usage. This is a result not only on miniaturization of the hardware components and their low prices but, also due to the development of novel control paradigms as well as development of Artificial Intelligence (AI). The growing popularity of the Artificial Intelligence (AI) and its application in various fields [1], starting from tourism [2], through medicine [3-5], biology [6], education [7], robotics [8-11], and also in economy [12], is mainly due to the apparatus i.e. the models and techniques used to mimic the human reasoning, learn and improve during time.

Research funds, crowd-funding platforms but, also commercials and news headlines are also an important indicator of the rising popularity of robotics in the recent years. Fifty years ago, almost nobody believed that humanoid robots, like Rosey the Robot Maid in the Jetsons animated series, may become true.

Nowadays, we can find multiple robot systems that have significant level of intelligence, used in our daily life. Examples include autonomous cars or unmanned aerial vehicles, various service robot systems, smart home appliances such as air-conditioning systems, automatic vacuum cleaners and many more.

The fact that our life is becoming more and more "robotized" as well as the possibilities to develop smart systems that may contribute to improve human live, is inspiring more and more students to gain knowledge and become robotics specialists.

As educators the first problem we have to face is to raise the awareness and change the students' attitude towards the technology.

Namely, being surrounded with technology since they are born, our students rarely perform a deeper analysis of its working principles. They often treat the technological devices as disposables without even considering the fact that they can be fixed upon failure. As a consequence, if we like to create active thinkers instead of passive users we should change and improve our education programs not only in high school but, also at the university level.

The course Fundamentals of Robotics, is part of the bachelor's curriculum at the Faculty of Computer Science at the University Goce Delcev in Stip, for more than 5 years.

Students tend to find Robotics very attractive, but they are also aware that it is a multidisciplinary area combining elements of physics, mechanics, electronics, and mathematics.

Our past experience shown that students often choose this subject in order to "play" with robots, disregarding that certain important concepts of Robotics require mechanical, mathematical or geometric background which they sometimes find troublesome.

One of the topics that are not so intuitive to be explained and to be perceived by the students are the concepts of forward [13,14] and inverse kinematics [15–17], which define the physical behavior of serial robotic chains. Solving kinematics problems requires knowledge from linear algebra, coordinate transformations, fundamentals of mechanics and a good spatial perception of the 3D movements that occur to the joints of the robots.

Understanding the geometry, kinematics and dynamics of serial robot chains using only written teaching resources can be very difficult for computer science students. Therefore, in the framework of this course we are complimenting the textbooks and ex-cathedra teaching methods with dedicated learning/teaching software that enables the students to easily create, visualize, and simulate the model of a robot in the CAD environment and spent more time to understanding its kinematics. It would also allow the course teacher to demonstrate the concepts and the robot motion in a classroom setup more conveniently. Lab exercises with physical humanoid robot are also part of the teaching methodology.

Main goal of this paper is to validate the adopted approach to teach the kinematics of serial robot chains using virtual environments and physical humanoid robot. Moreover, the concept of visual programming of serial robotics chains vs. classical programming has also been evaluated.

II. BASICS OF ROBOT KINEMATICS

Serial robot chains are designed as a series of links connected by motor-actuated joints that extend from the origin to an end-effector. The joints can either be very simple, such as a revolute joint or a prismatic joint, or else they can be more complex, such as a ball and socket joint. Serial robot chains are integral part of various types of robot systems, from industrial to service robots. Therefore, solving the problem of direct (or forward) kinematics and the problem of inverse kinematics is fundamental for their control and application.

The forward kinematics problem is concerned with the relationship between the individual joints of the robot manipulator and the position and orientation of the tool or end-effector. Stated more formally, the forward kinematics problem is to determine the position and orientation of the end-effector, given the values for the joint variables of the robot.

The joint variables are the angles between the links in the case of revolute or rotational joints, and the link extension in the case of prismatic or sliding joints. The forward kinematics problem is to be contrasted with the inverse kinematics problem, which is concerned with determining values for the joint variables that achieve a desired position and orientation for the end-effector of the robot.

A. *Forward kinematics*

The kinematic analysis of an n-link manipulator can be extremely complex and usage of some conventions can significantly simplify the analysis and contribute towards building a universal language by the means of which engineers can communicate.

A serial robot chain with n joints will have n + 1 links, since each joint connects two links.

The joints are usually marked with numbers from 1 to n, and the links from 0 to n, starting from the origin. Using this convention, one may say that the joint i connects link $i-1$ to link i. It can be also assumed that the location of joint i is fixed with respect to link $i-1$. When joint i is actuated, link i moves. Therefore, link 0 (the first link) is fixed, and does not move when the joints are actuated. Of course the robot chain could itself be mobile (e.g., it could be mounted on a mobile platform or on an autonomous vehicle), but this case becomes trivial for explanation if the logic is well understood.

In the 1950s, Denavit and Hartenberg [18] used screw theory to prove that the most compact representation of a general transformation between two robot joints required four parameters.

These are now known as the Denavit and Hartenberg parameters (D–H parameters) and they are the de-facto standard for describing the geometry of a robot [19]:

1. Perpendicular distance between two joint axes, measured along the x axis.
2. Relative twist between two joint axes, measured about their mutual perpendicular vector.
3. Distance between the perpendicular vectors of two joints, measured along the axis of the first one.
4. Joint angle between the perpendicular vectors of two joints, measured about the z axis.

In practical terms, these four parameters can be re-described using the local axes of two

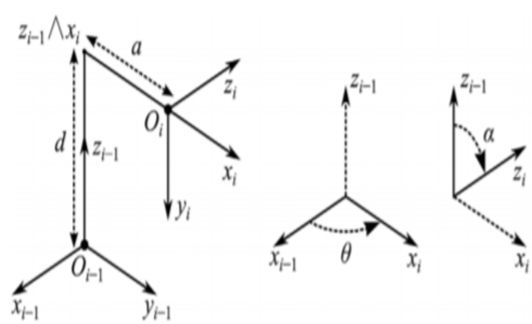

Figure 1. *Denavit – Hartenberg parameters*

neighboring joints or interest points.

Be vectors x_i and z_i the local x and z directions of the i^{th} joint, located at position O_i; vectors and x_{i-1} and z_{i-1} those of the previous joint, located at O_{i-1}; and $z_{i-1} \wedge x_i$ the intersection point between vectors z_{i-1} and x_i (Fig. 1), the D–H parameters can be summarized as follows:

- Distance from O_{i-1} to $z_{i-1} \wedge x_i$, measured along z_{i-1}.
- Relative twist from x_{i-1} to x_i, measured about z_{i-1}.
- Distance from $z_{i-1} \wedge x_i$ to O_i, measured along x_i.
- Relative twist from z_{i-1} to z_i, measured about x_i.

Students are encouraged to use the "right hand rule" in order to figure out the sign of the twist parameters: By placing the thumb of their right hand in the direction of the rotation vector, angles α and θ will be positive only if they correspond to the angle in which fingers curl. For instance, on Figure 1, θ would be positive and α would be negative.

Auxiliary coordinate axes simplify exercises at the expense of increasing the amount of required calculations. Students are often allowed to make their own decision regarding how to solve incompatibility situations, since both axis rearrangement and auxiliary axes are equally valid approaches and produce equivalent results.

Once the D–H parameters have been calculated, the forward kinematics problem can be solved by transforming the joint reference systems, from the base of the robot to the end effector, through geometric transformation matrices:

$$^{i-1}T_i = \begin{bmatrix} \cos(\theta_i) & -\cos(\alpha_i)\sin(\theta_i) & \sin(\alpha_i)\sin(\theta_i) & a_i\cos(\theta_i) \\ \sin(\theta_i) & \cos(\alpha_i)\cos(\theta_i) & -\sin(\alpha_i)\cos(\theta_i) & a_i\sin(\theta_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

defines the translation and rotation from joint i to joint i-1. Be O_N the hypothetical joint located at the end effector, its homogeneous spatial coordinates relative to the robot basis (i.e., joint O_0) can be calculated as:

$$^0T_N \bullet O_N = \left(\prod_{i=1}^{N} {}^{i-1}T_i \right) \bullet [0 \quad 0 \quad 0 \quad 1]^T \quad (2)$$

since $^iT_j \cdot {}^jT_k = {}^iT_k$ and the homogeneous coordinates of any spatial point relative to itself are always $[0,0,0,1]^T$.

The spatial coordinates of every point O_i of a robot chain can be calculated in the same way, by multiplying all the transformation matrices up to said point, times the homogeneous zero coordinates.

B. Inverse kinematics

The general problem of inverse kinematics can be stated as follows. Given a 4 × 4 homogeneous transformation:

$$H = \begin{bmatrix} R & o \\ 0 & 1 \end{bmatrix} \in SE(3) \quad (3)$$

with R ∈ SO(3), find (one or all) solutions of the equation

$$T_o^1(q_1, q_2, \ldots q_n) = H \quad (4)$$

Where

$$T_o^1(q_1, q_2, \ldots q_n) = A_1(q_1)A_2(q_2)\ldots A_n(q_n) \quad (5)$$

Here, H represents the desired position and orientation of the end-effector, and our task is to find the values for the joint variables $q_1, \ldots, q_n$ so that $T_o^1(q_1, q_2, \ldots q_n) = H$.

Unlike forward kinematics problem which has a unique solution, inverse kinematics problem of a typical serial robot chain is not straight forward, mainly, owing to the existence of multiple solutions of the highly non-linear trigonometric functions. While the forward kinematics has a generic procedure for all robot architectures, there is no generic inverse kinematics solution possible that can accommodate all robot architectures.

One has to resort to a numerical algorithm for the solution of corresponding kinematic constraint equations. To obtain solutions to the inverse kinematics problem, one is required to solve multiple multivariate transcendental equations. Sometimes no solution may exist for a given input pose. Such aspects make the topic of inverse kinematics relatively difficult in an introductory course on robotics.

III. Methodological Approach

The topic dedicated to kinematics of serial robot chains is part of the course Fundamentals of robotics subject, during the fourth year of the Computer Engineering and Technology Degree. This subject has been scheduled to cover six credits, according to the European Credit Transfer and Accumulation System (ECTS), which correspond to 156 work hours. This load is divided into three ECTS theory credits and three ECTS laboratory credits.

During the lecture hours, students are introduced to the theoretical and mathematical aspects as well as with robot programming aspects. During laboratory hours, the students are taught how to program and control physical robots using standard and visual programming environments. Moreover, laboratory exercises promote the development of teamwork skills and favor the voluntary formation of work groups inside and outside the classroom.

In order to facilitate the solution of the direct and inverse kinematics problems they were first explained by simulation using RoboAnalyzer 3D simulation environment [20]. This way the students were able to overcome various constraints such as: limited number of physical robots, capability to test and experiment for a limited and fixed number of hours and only during working days etc.

This simulation environment also helps students to:

- build any type of serial-link manipulator and visualize it in 3D.
- change the position and orientation of the joints of the robot through the use of sliders, which helps them to improve their ability of understanding orientation and positioning in 3D spaces.
- change the orientation of different reference frames associated to each joint, which helps them calculate Denavit–Hartenberg related parameters.

Since the inverse kinematics of a serial robot chain, depends heavily on the 3D structure of the robot, and is therefore extremely difficult to automatize simulation models with an architecture similar to the humanoid limbs were created and analyzed in RoboAnalyzer.

Once the basic kinematics concepts were understood, all student team were asked to apply this knowledge on humanoid robot limbs.

For this purpose, the humanoid robot Alpha 1S (Figure 2) was used. The robot is made of Aluminum alloy structure with ABS housing, it weighs 1.65kg, and has dimensions of: 401*198*124mm.

The robot was programmed via Bluetooth protocol using standard programming environment as well as using custom visual programming environment (Figure 3).

Visual programming interface is also offering a possibility to have a 3D preview of the actions performed by code sequences designed by the programmer.

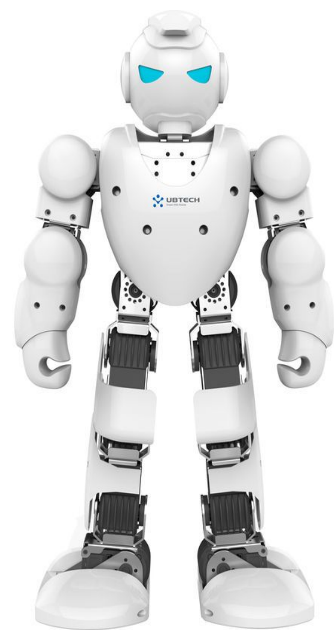

Figure 2. *Alpha 1s humanoid robot*

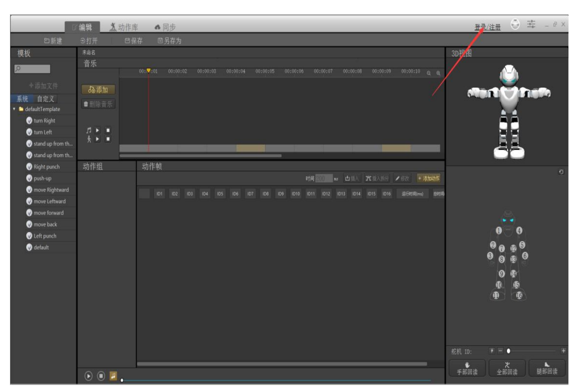

Figure 3. *Visual programming environment*

IV. Evaluation

At the end of the semester students were asked to perform two types of tasks with the humanoid robot: first one was to calculate the position of the end effectors of humanoid limbs for a given configuration of its joints i.e. a task that corresponds to the forward kinematics problem, and the second task was to calculate the configuration of various joints of humanoid robot limbs in a way that their end effectors will be positioned in a specific point.

All 10 student groups, composed of 3 members have successfully completed both tasks. They were asked to respond to a set of questions related to the course methodology.

Each student gave a mark to each of the questions, from 0 (fully disagree), 1 (disagree), 2 (agree) and 3 (fully agree). The mean result obtained at each of the questions together with the related standard deviation are presented in the Table 1.

Figure 4. *Group of students at the Faculty of Computer Science, University Goce Delcev Stip during their laboratory excersises*

TABLE I. EVALUATION QUESTIONS AND ANSWER RESULTS

No	Evaluation questionnaire		
	Question	***Answer avg.***	***STD***
1	Do you regard the humanoid as a useful tool to understand the direct/inverse kinematics of serial robotic mechanisms?	4.1	0.99
2	Do you find the development environment easy to use?	4.7	0.60
3	Do you find the graphical capabilities of the development environemnt useful to understand the direct and inverse kinematic problem?	3.6	0.88
4	Do you find the videos enclosed in the laboratory sessions helpful to accomplish the tasks?	4.8	0.48
5	Do you find the documents that come along each laboratory session helpful to understand the practical sessions?	4.8	0.48
6	In general, do you think that the humanoid robot has helped you to understand the concepts explained during theory lessons?	4.1	0.62
7	Do you find the course organization approriate?	4.7	0.60
8	Would you recommend this course to future students?	4.8	0.5

V. CONCLUSION

Main goal of this paper is to validate the adopted approach to teach the kinematics of serial robot chains using virtual environments and physical humanoid robot. Moreover, the concept of visual programming of serial robotics chains vs. classical programming has also been evaluated.

The results of the evaluation showed that methodological approach of the course is appropriate and that the course is very exciting for students. Further discussions with students revealed the fact that motivation tasks and team-working were very inspiring and useful.

Using humanoids to teach direct and inverse kinematics was also considered a good approach. Students preferred to use the visual oriented development environment in contrast to the traditional one for their projects. However, their main concern was regarding the graphical user interface of the development environment. This was mainly due to its very complex structure and it was marked as not user-friendly by the students.

In summary, the fact that the students would recommend this course to their younger colleagues is a sort of justification of the methodological approach.

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