UNIVERSITY OF ZAGREB

FACULTY OF ELECTRICAL ENGINEERING AND COMPUTING

SEMINAR

Humanoid Robot Motion Control

Ivana Mesić

Mentor: Assistant Professor Ivan Marković, PhD

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INTRODUCTION

Robotics and automation have greatly changed the modern world and are still developing very rappidly. Robots today represent a big part of the work force and it is expected that until 2025 they will perform about 25% of all the working tasks[1]. However, humanoid robots still are not included in this percentage. Although today they are popular with the public thanks to their exciting look and impressive abilities, they are still not in commercial use as some other types of robots, but they have a great potential for growth and widespread use.

Humanoid robots are one of the newer, but at the same time fastest growing branches of robotics. Even though their development has started only several decades ago, they are expected to be widely spread in the future. Some experts think that they will develop so quickly that in 2050 there will be a team of humanoid robots possessing such motoric skills that they would be able to beat the reigning Football World Cup champions. Today, this goal is still far from reality because scientists, engineers and researchers are still trying to find optimal solutions to some of the main problems in robot modelling and construction.

What exactly are humanoid robots? Humanoid robots get their name because their main purpose is to imitate humans. Most of them try to imitate the human figure, with two ”legs“ and movements like walking, and some of them try to even imitate human facial expressions. Some of the main characteristics that humanoid robots have in common are machine learning, sustainability, computer vision and environment interaction. Some of their main components are sensors that are used for orientation and registering objects and actuators, which are responsible for the motion and movement of robots[2].

The development of humanoid robots greatly differs from all the other branches of automation and robotics because researchers and engineers have to consider the social and ethical components of human-robot interaction, as well as its technical component. Currently, there are not many humanoid robots on the market since their production and development are ong and very expensive. There are not many models in commercial production, but newer models are being developed on many different projects at universities or in research centres of technical companies and they vary in size, appearance and abilities.

It is important to consider the history of humanoid robot research to compare the speed of their development. The University of Tokyo's WABOT-1 is considered to be the beginning of humanoid robots[3]. Its abilities were impressive for its time: it had a locomotion system with touch sensors, a vision system that could measure distances and could communicate in Japanese at a two-year-old child's level. The next great breakthrough was the unveiling of ASIMO 2000. Its influence transcended the boundaries of the robotic and scientific community, because it attracted the attention of the broader public and consequently stimulated humanoid robot research and development. Today, there are many models featuring impressive skills, however many experts believe that current models do not meet expectations and that there is still a long way ahead in their development.

One of the main aspects that engineers consider when developing a humanoid robot is their purpose and use. Depending on their use, engineers focus more on the robot's motoric skills or its artificial intelligence. The conceived purpose of humanoids is to replace humans in jobs that are dangerous or hazardous, such as working in nuclear plants, handling explosives or rescue efforts during natural disasters. They could also be used as assistants to humans in jobs like care for the elderly, educational purposes and as emotional support, or completely replace humans in jobs like a receptionist or a job interviewer[4]. Some scientists also include the possibility of conducting neuroscience research on humanoids, because brain models could be implemented using AI technology. There are many fields of work where humanoids would be useful and there could still be many usages of these robots that have not yet been thought of.

It is very hard do develop a humanoid having many different functionalities because it needs to have highly developed motor skills, balance, real-life object recognition and computer vision to perform any human-like task and these are all still mostly in the stage of research. So instead of developing all the components simultaneously, engineers usually focus on one area to perfect it completely (e.g. motor skills) and neglect others (e.g. sound recognition)[5]. In this seminar, the focus will be on robots that were developed for the purpose of perfecting their locomotion system, as well as systems that provide support to the robot's autonomous orientation such as sensor systems and object recognition.

SEMINAR

Types of Humanoid Robots

Humanoids are developed on individual projects in research centres and are still not in commercial production. Therefore, it is hard to define the types of these robots because each model can significantly differ from others. Almost all the developed humanoids are still used for research purposes only, and embody the technical progress achieved by the engineering teams that created them.

Although they are different, some models of humanoids could be grouped together based on their similar characteristics. For example, we could single out SoftBank robotics' Nao, Aldebaran's Romeo and Poppy robot. They are up to 1 m tall and can mimic human movements like walking, dancing or balancing on one foot. They are used in different fields, such as education for children, cheering up patients in hospitals and as entertainment. Nao was developed especially for educational purposes and was tested in some schools in the United Kingdom where it helped autistic children. It is also used at secondary schools and universities as introduction to robotics and programming courses.

Picture 1: Nao robot

On the other hand, Nao's ”bigger brother“ Romeo was intended to be an elder's house assistant. It was supposed to be a bigger version of Nao with similar abilities that would help elderly people with house chores and provide some kind of companionship. During Romeo's construction, the researchers were faced with some of the most common challenges in humanoid robot development and modelling. Romeo was supposed to be a bigger version of Nao, but with height came additional weight and the need for bigger motors. The added weight created problems with balance and more difficult movements, which are some of the main challenges in robot motion control. This also shows that although engineers found a solution to a certain type of robot it cannot always be applied to all the other models because their movements depend greatly on their size and weight[6].

UBTech's Walker model is a newer model having a similar purpose as Romeo. It has shown great motor skills, but for the time being in controlled conditions. Although UBTech promotes it as an “indispensable part of the family“, it is still far from it because it still has deficiencies in self-recovery after a fall and self-navigating movement[7].

Other types of robots that could be grouped together are robots developed with an emphasis on their locomotion system. A wide range of robots of this type were introduced during the *DARPA Robotics Challenge* competition, which was created to promote the development of ”first responders“ humanoids that could be used during fires, earthquakes and similar natural disasters, as well as nuclear disasters especially hazardous for humans[8]. During the final competition, 25 different robot models were presented. The robots were tested with a series of human-like locomotion tasks such as opening doors, driving a vehicle, climbing stairs or drilling holes in a wall. All of the robots had a similar appearance, they were about 180-190 cm tall and their weight differed greatly (60-190 kg).

Picture 2: Boston Dynamics' ATLAS

One of the presented models was Boston Dynamics' ATLAS robot, which has since been greatly improved and is one of the most developed humanoids today. It was named the most dynamic robot ever because it can perform a number of tasks that could not be performed by previous humanoids. It can walk and run even on uneven terrains such as woods or rocks, jump over obstacles with one or both legs and move sideways, all while navigating autonomously[9]. One of its most impressive skills is its ability to perform a back-flip, which may not be one of the most useful skills it has, but definitely demonstrates the improvement in its performance.

Honda E2-DR is another robot designed for rescue missions under extreme conditions. Honda E2-DR can perform some complex tasks (although not very fast) like climbing stairs and hanging ladders, moving debris from the ground, moving through and adjusting to narrow spaces. Furthermore, it can endure the rainfall for a limited period of time without damage to its hardware[10]. This model also shows tremendous software developments, because it perceives its surroundings by itself, registers obstacles and finds solutions on how to overcome them. One of its main deficiencies is its inability to endure and recover from high falls, which could happen during climbing.

Digits is one of the rare examples of robots in commercial use that have a high performance locomotion system. Its creators suggest that it will completely revolutionise delivery of all sorts and could reduce the need for self-driving vehicles. This model will be put up for sale in 2020[11]. One of the reasons for its expected popularity is its developed "hands" with four degrees of freedom, which is very advanced in comparison to other models.

The last group of humanoids, maybe the most exciting one for the public, are the humanoids with highly developed artificial intelligence. During the development of these models, scientists and engineers must include the social aspect and need to conduct not only technical, but also social experiments to optimise their interaction with humans[12]. One of the best known models is Sophia that has a realistic human face and robot body and is one of the most advanced examples of artificial intelligence today. It can fluently communicate with humans and detect human voices even when there are multiple voices talking simultaneously. It uses computer vision to recognise and differentiate human faces and objects[13]. Although its development does not put an emphasis on the locomotion system, it shows some great improvements such as facial movements and its control system.

Picture 3: Humanoid robot Sophia

Challenges in Motion Control Design

The structure of robots sets some limits so they cannot exactly replicate human movements. It is still impossible to create a humanoid robot with a locomotion system of the same complexity as a human because the human locomotion system consists of hundreds of intertwined bones and muscles that work (in synergy?) cohesively. The main focus in developing humanoids has been to perfect their ability to walk.

Humanoids use a bipedal system to walk. Bipedal systems are mostly based on the Zero-Moment-Point (ZMP) theory. ZMP is defined as a point on the ground where the net moment of the inertial and gravity forces has no component along the axes parallel to the ground. The trajectory of ZMP plays an important role in balancing the robots while walking. For a feasible walking pattern, the ZMP trajectory must lie within the supporting polygon defined by the location and shapes of the supporting feet[14]. For this reason, most humanoid models have wide feet to facilitate keeping their balance.

One of the main challenges in ZMP theory is that the foot of the robot must be on the ground with its full surface for the ZMP to be accomplished. That presents a challenge when the robot is moving on uneven terrains such as rocks, pebbles or sand. However, ATLAS and ATRIAS models have successfully adapted to such challenging conditions using some newer technology[15]. ATLAS uses the LIDAR sensor system that scans the terrain on which the robot is moving and creates a map of planar regions to the goal location, while ATRIAS does not have sensors and relies solely on its ability to keep its balance while it moves. The problem with sensor systems is that they cannot always scan the terrain completely (for example when there are indentations that are too big to register with sensors) and when that happens the robot cannot move because it cannot create its path-planning trajectories. On the other hand, the deficiency of the no-sensor system is that the robot cannot move along predefined trajectories or perform predefined movements[16]. The goal is to combine these two types of motion control and enable the robot to move on uneven terrains as well as perform predefined motions.

The biggest challenge faced by robots while moving is keeping their dynamic balance. Humans do not think about keeping their balance, but it is very hard to accomplish this with robots, and this problem is one the major preoccupations of engineers in the implementation of humanoid locomotion systems. The ATLAS model has one of the best systems for keeping balance. Its centre of mass is calculated dynamically based on the current position of the robot and the weight of some robot parts, and the centre of mass is kept within predefined limits that ensure that the robot is in balance. Changing the configurations of the robot's joints results also in recalculating its center of mass and setting constraints to assure the center of mass is kept within safe limits.

In addition to the execution of the locomotion system, the robot's navigation is also a big challenge in their production. Robots depend on computer vision using advanced cameras and sensors, but the problem is the analysis of large amounts of data, which they have to process in real time to determine their movement trajectories and to recognise potentially harmful objects. What they see can greatly influences their moving trajectories. Not only do they have to visualise the terrain, but they have to recognise the impact that certain objects or areas can have on them and choose whether to avoid them accordingly. For example, a human will know how to avoid a puddle because otherwise they will get wet, but for the robot this action presents a greater challenge. It has first to recognise that the area it sees is actually a puddle and to determine that it can be harmful, then it has to recalculate its motion so that it bypasses it, which could potentially be more difficult than to just step in it. It is crucial that the robots computer vision and sensors can operate fast because this is only the first in a number of steps enabling the robot to move smoothly, so delays in vision and its processing result in delays in the later phases of motion control.

It is something of a paradox that the improvement in dynamical abilities creates new deficiencies, because adding new parts and apparatus that can improve robot's movements increases the weight of the robot and reduces its agility and ability to balance. There is still room for improvement in these areas in order to perfect humanoids' dynamic abilities.

Motion Modelling

With present-day technology it is still impossible to create a robot featuring a wide spectrum of movements that humans have. Therefore, robots have a limited number of movements that engineers then try to perfect. For most models, the goal is to be able to walk, run and jump using a bipedal system while adjusting to the terrain and without loosing its balance, and perform multiple tasks with their "hands". Their joints have restricted degrees of freedom, which limits their range and flexibility.

During research and construction of a humanoid, engineers first study human movements and dissect them in order to better understand them and apply them to the robot more easily. This process can be difficult because most of the movements that humans do are natural to them and do not require thinking and planning. In reality however human movements are extremely complex and have many factors influencing them. Motion modelling represents a collection of methods, the purpose of which is to try to understand the principles of movement and modify them so that they can be applied to the humanoid.

Motion modelling includes the digitalization of movements, which first need to be collected and mapped so that they accurately mimic human movements. Some of the methods used for collection of this data are sensors or infrared-based or continuous camera tapes that are then analysed. It is important for the robot to know movement sequences in great details. It needs to know which action is currently performed, which action follows, what its surroundings is like and what the anatomical characteristics of the object it is working with are like. A way to collect this data is to analyse each movement and track parameters like step width, joint positions, waist height or placement of some components. This data is later processed using complex algorithms and applied to the robot's computer. The algorithms processing the data are created using inverse kinematics, which is a process determining joint configuration based on the known desired action. The inverse kinematics methods that are sometimes used with industrial robots do not always apply to humanoids because they produce sets of equations to reach the final destination. These equations produce movements that are not entirely human like so they do not always produce the best possible solution.

The algorithms used for motion control greatly depend on the part of the robot that has to be moved. Most of the methods are pose-oriented or task-oriented. The pose-oriented approach optimises the robot's movements to make them as human-like as possible. In this approach, the robot creates and plans its own movement sequences based on the assignment it has to perform. With this approach, it is harder for the robot to interact with and handle foreign objects because this does not allow a precise configuration and positioning of the robot's end effectors. Therefore, this approach is not used when the robot should be dealing with objects or interacting with humans, but is used instead for movements like walking and jumping where the exact positioning is not so important. On the other hand, the task-oriented motion algorithms differ from the pose-oriented ones, because their main focus is on the task that needs to be performed rather than on the poses made during the process.

Current methods used to generate a pose- or task-oriented motion are methods that map a given human motion trajectory for the robot, and model-based approaches.The difference between them is that model-based methods rely on the knowledge of human behavior that allows them to independently generate entire trajectories, while the mapping of human motions requires some explicitly given trajectories from motion capture data[17]. Model-based methods are mostly used for bipedal walking or running because they require the control of the entire body and require a whole-body mapping.

Picture 4: Motion mapping using model based approach

An example of model-based methods is presented with the Nao robot model. A set of sensors is set on a human that enable the robot then to replicate human's poses and movements. The robot receives the data from the sensors 30 times in a second and gets joint configurations then using the methods of inverse kinematics. A problem arises when there is a possibility for the robot to loose its balance while recreating a pose because of the difference in the mass distribution in its components in comparison with the human body. In this situation, active stabilisers can be used that restrict movements of the upper part of the robot's body and thus ensure that it does not lose its balance.

Recently, a new approach has been suggested, called the context-oriented approach,[18] that would combine the pose- and task-oriented approaches. The process motion context is determined by the motion planner and consists of the task, the pose and the style of the motion (fast, slow, precise etc.). From the given task, the motion generator would create a set of trajectories that could complete the task. The set of trajectories is then classified using a motion classifier and a final trajectory is chosen that best suits the predefined pose and style constraints. This approach is yet to be researched and implemented.

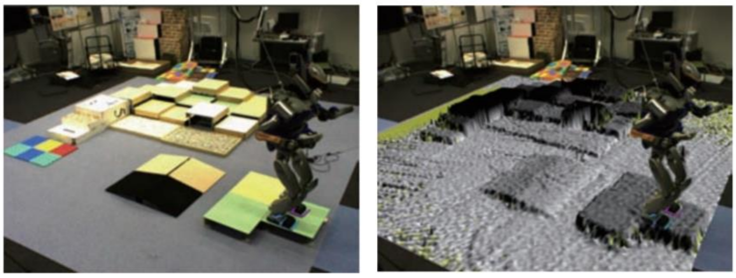
Current Motion Control Solutions

One of the current motion control technologies is GIK or Generalised Inverse Kinematics. Its main idea is to prioritise dynamic walking (walking with keeping dynamic balance), because keeping balance is the robot's main concern. Losing its balance presents multiple challenges to the robot like hardware damage or the inability to recover because this is an unknown situation for it. For the implementation of dynamic walking, two tasks are created: controlling the centre of mass and controlling the stepping foot. The idea of GIK is to generate a list of tasks that the robot has to perform and to set a number of constraints for each task that will ensure the robot does not lose its balance. GIK then uses inverse kinematics to determine joint configurations that will enable the robot to perform its task[19].

A method of motion control is the aforementioned model-based approach that is implemented in some models. The robot's movements are controlled by a human in real time using sensors, which enable the robot to imitate the human's movements. This solution, although extremely important in motion mapping and teaching the robot human like-movements, is not suitable when the robot is finished, because it should be able to operate on its own, using its own navigation and planning its own motion.

Today, most robots use variants of the ZMP theory in motion control on uneven terrain. There are two types of approaches: with and without terrain modelling.

Methods without terrain modelling lower the complexity of control systems. With this approach, robots do not plan their movements based on the obstacles in the surroundings, but rather try to resist negative consequences while moving into the unknown. The potential to maintain original gaits is actually lost, because these methods are not specific to the conditions of the terrains. Variable walking parameters like step length and walking cycle period are modified, which might leave less margin for resisting other disturbances. In these methods, walking is stabilised by body acceleration, body rotation or foot landing point adjustment.



Picture 5: Terrain map

Robot models that use terrain modelling have to be equipped with special sensors in order to perceive their surroundings and to adapt to it. Not only should a robot plan and choose the trajectories along which it will move, but it should also adapt the positioning of its body to fit the space in which it moves. Today, movement of humanoid robots using autonomous navigation consists of a number of steps or phases. The first step is perception of the terrain on which the robot should move. During this phase, the robot uses laser sensors and cameras that first perceive space as a 2D surface and later on perceive its depth and configurations. The product of this phase is a terrain map (in the picture) that consists of a grid of cells in which each cell has a height value. The obtained terrain map is then used in the second phase, footstep planning. During this phase, the footstep planner generates a number of possible stepping positions, taking into account the configuration of the terrain and distance of the stepping foot from the standing foot. The next phase is the generation of a walking pattern, during which the trajectories of the torso and feet are created. Thereafter, the walking controller ensures that the generated walking pattern is dynamically stable and that the robot will keep its balance while performing these movements. The walking controller sets constraints on trajectories if needed and then they are transformed using inverse kinematics to get the final joint configurations. The robot's motors then set the joints to defined configurations and the robot performs the planned movement[20].

So far, the biggest problem with the terrain modelling approach was creating an accurate terrain map in a short landing period. One of the problems is that sensors must cover a wide area in front of the robot, but the sensors that can do that cannot perceive the depth of the terrain entirely accurately. Furthermore, elastic deformations of the legs reducing the reliability of the kinematics should be taken into consideration when moving on an uneven terrain[21]. There is still a lot of room for improvement in this area.

CONCLUSION

Humanoids of today still do not have the motoric skills needed for them to successfully perform their designated tasks. It is imperative to invest in their further development and research. They have a great potential to improve society and replace humans in some jobs that unnecessarily put them at risk. Although some newer models show impressive abilities, there is still a lot of room for improvements, especially in the locomotion system of humanoids.

In this seminar, many challenges in the motion control of humanoid robots have been pointed out. One of these challenges is the ZMP theory on which many models still rely, which has deficiencies and does not always make sure that the robot keeps its balance. Another problem is the use of inverse kinematics in determining joint configurations because sometimes produced movements are not human-like. The context-based approach to motion modelling is a way to ensure the robot's movements are human-like while it also performs the needed movement.

Another aspect that also needs to be improved is the terrain modelling of uneven terrains. In motion control, the complete perception of space is crucial because it influences the choice of trajectories the robot will take, based on the shape of the terrain. Better sensors would allow the creation of more precise terrain maps, which would greatly improve the robot's navigation and motion control. Although there are models of robots that do not use terrain modelling, they are less complex and cannot perform all the actions that those that use it can. After all, the goal is for humanoid robots to be as human-like as possible, so terrain mapping is crucial for them to perceive the surroundings, identify potentially dangerous areas and avoid them, as humans would. Therefore, this approach and motion control in humanoids in general have to be further researched and developed.

SUMMARY

The development of humanoid robots is of great value to society, because the wide use of humanoids could greatly improve human life. Some of their main applications could be replacing humans in dangerous jobs or working as assistants to elderly people or children. For this to happen, many improvements have to be made in their construction and abilities, primarily in their locomotion system.

Although there are many humanoid model types, developed in research projects all over the world, they could be grouped based on their similar characteristics. There are smaller robots that are meant to be used in education or as emotional companions; there are bigger ones that have highly developed motor skills and are meant to be “first responders”; and there are ones in which the emphasis is not on their movements but rather their advanced artificial intelligence and human interaction.

One of the biggest challenges facing engineers is the construction of the locomotion system of humanoid robots. Some of the problems in this regard are keeping balance, moving on uneven terrain and constructing a bipedal system that has straight legs as humans do. Although far from ideal, the ATLAS model produced by Boston Dynamics presents some of the best solutions for these problems today. Its use of the LIDAR system enables it to perceive its surroundings and uneven terrain and plan its moving trajectories accordingly. Some of the challenges still not solved are registering bigger indentations in the ground, preparing for them accordingly as well as recovering from a fall.

During the construction of motion control systems for humanoid robots, the first step is to explore the human motion in order to be replicated by robots. Human movement can be digitalised using motion capture, or data can be analytically collected in order to store it in the robot. The robot can later use that data to set its joint configurations and recreate human-like motion. One of the solutions is the GIK software that prioritises walking and sets constraints in order to keep the robot in balance.

Today, motion control in robot models is composed of phases in which the robot first perceives the terrain and creates a terrain map, then calculates all of the possible steps it can make and then chooses the optimal step taking into consideration the configuration of the terrain. During this process, controllers are used to keep the robot’s balance and to restrict some movements so it does not jeopardise it.

Although the abilities of some humanoids today are impressive and there has been a great improvement over the last decade, there is still a long way to go in the development of humanoid robots. Their motion control systems and motion planning are among the biggest challenges in their creation and should be the subject of much further research in order to improve their dynamic and motoric skills.

LITERATURE

Picture 1: Nao Robot; https://robots.nu/en/robot/Nao; 18.04.2019

Picture 2: Boston Dynamics' ATLAS; https://www.bostondynamics.com/atlas; 10.05.2019

Picture 3: Humanoid robot Sophia; https://medium.com/@tharanignanasegaram/sophia-a-real-live-electronic-girl-b40baca10a27 ; 10.05.2019

Picture 4: Motion mapping using model-based approach https://ieeexplore.ieee.org/document/6249599/figures#figures; 16.05.2019

Picture 5: Terrain map; K. Nishiwaki, J. Chestnutt; Autonomous Navigation of a Humanoid Robot on Unknown Rough Terrain; http://www.isrr-2011.org/ISRR-2011/Program_files/Papers/Nishiwaki-ISRR-2011.pdf; 16.05.2019

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[1] Gonzales, C.; What's the Future Role of Humanoid Robots?; 27.10.2017 https://www.machinedesign.com/motion-control/what-s-future-role-humanoid-robots; 14.04.2019.

[2] Humanoid Robots : An Overview; https://www.engineersgarage.com/articles/humanoid-robots; 14.04.2019.

[3] Fukuda, T., Dario, P., Yang, G. Z.; Humanoid Robotics—History, Current State of the Art, and Challenges; 20.12.2017;https://robotics.sciencemag.org/content/2/13/eaar4043.full?intcmp=trendmd-rob ; 14.04.2019.

[4] Crowe S.; Humanoid Robots: Five to Watch in 2019; 29.01.2019; https://www.therobotreport.com/humanoid-robots-watch-2019/; 14.04.2019.

[5] Fukuda, T., Dario, P., Yang, G. Z.; Humanoid Robotics—History, Current State of the Art, and Challenges; 20.12.2017; https://robotics.sciencemag.org/content/2/13/eaar4043.full?intcmp=trendmd-rob ; 18.04.2019.

[6] Romeo- A Helpful Friend for the Future; https://www.maxonmotor.com/maxon/view/application/Romeo-A-helpful-friend-for-the-future;
18.04.2019

[7] Ackerman, E.; UBTech Shows Massive Upgrades to Walker Humanoid Robot ; 08.01.2019; https://spectrum.ieee.org/automaton/robotics/humanoids/ubtech-upgrades-walker-humanoid-robot; 18.04.2019.

[8] DARPA Robotics Challenge; https://www.darpa.mil/program/darpa-robotics-challenge; 10.05.2019.

[9] Haridy, R.; Boston Dynamics' Atlas Has Now Mastered Parkour; 12.10.2018; https://newatlas.com/boston-dyanamics-atlas-parkour-running-jumping/56739/; 10.05.2019.

[10] Ackerman, E.; Honda Unveils Protoype E2-DR Disaster Response Robot; 02.10.2017; https://spectrum.ieee.org/automaton/robotics/humanoids/iros-2017-honda-unveils-prototype-e2dr-disaster-response-robot; 10.05.2019.
[11] Dent, S.; The Digit Robot Could be the Future of Pizza Deliveries; https://www.engadget.com/2019/02/27/the-digit-robot-could-be-the-future-of-humanoid-pizza-deliveri/?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuZ29vZ2xlLmNvbS8&guce_referrer_sig=AQAAAFzXVPEMkJDZcOITHdZIOTSAC8hRy1rG6v5K8fsme2Ude1m1MwmTsXvAROfFuTJA3aQt5LC6eG10CWQZ1W6ZVX_lC1As2fXb3C3QRwpGnMZQ8Fi_JUVK-oj99LJbbbVBlMgG1CcrPTwtwfD3MVjhIXYUkTQjcQ9DQlIKwsFnWtIB; 10.05.2019.
[12] Guner, S.; The Rise of Humanoids: The Future is Here; 27.12.2018; https://www.dailysabah.com/science/2018/12/27/the-rise-of-humanoids-the-future-is-here; 10.05.2019.

[13] Stone, Z.; Everything You Need to Know about Sophia; 07.11.2017; https://www.forbes.com/sites/zarastone/2017/11/07/everything-you-need-to-know-about-sophia-the-worlds-first-robot-citizen/#63852dde46fa; 16.05.2019.
[14] Ting, C., Yeo, W. H., Yeong-Jin K.; Humanoid Robot: A Review of the Architecture, Applications and Future Trend; Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, Kuala Lumpur; 20.02.2014.
[15] Ackerman, E.; IHMC Teaches ATLAS to Walk like a Human; 5.12.2018; https://spectrum.ieee.org/automaton/robotics/humanoids/ihmc-teaches-atlas-to-walk-like-a-human; 14.05.2016.
[16]Cohen N.; Atlas is Rockstar Cross-Stepper over Tricky Terrain; 11.03.2019.https://techxplore.com/news/2019-05-atlas-rockstar-cross-stepper-tricky-terrain.html; 14.05.2019.

[17]Stein T., Fischer A., Boes K., Wank V., Boesnach I., & Moldenhauer J.; Guidelines for Motion Control of Humanoid Robots: Analysis and Modeling of Human Movements; 2007; 13-15;
[18] Stein T., Fischer A., Boes K., Wank V., Boesnach I., & Moldenhauer J.; Guidelines for Motion Control of Humanoid Robots: Analysis and Modeling of Human Movements; 2007; 13-15;
[19] Sreenivasa, M.; Modeling of Human Movement for the Generation of Humanoid Robot Motion; PhD thesis; Institut National Polytechnique de Toulouse; 2010.
[20] Nishiwaki, K. and Chestnutt, J.; Autonomous Navigation of a Humanoid Robot on Unknown Rough Terrain; http://www.isrr-2011.org/ISRR-2011/Program_files/Papers/Nishiwaki-ISRR-2011.pdf; 16.05.2019.
[21] Yi, J., Zhu, Q., Xiong, R. & Wu, J. Walking Algorithm of Humanoid Robot on Uneven Terrain with Terrain Estimation; 2017; 1-5