A Human-Like Robot Torso ZAR5 with Fluidic Muscles: Toward to a Common Platform for Embodied AI

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Abstract. "Without embodiment artificial intelligence is nothing." Algorithms in the field of artificial intelligence are mostly tested on a computer instead of testing on a real platform. Our anthropomorphic robot ZAR5 (in German Zwei-Arm-Roboter in the 5th version) is the first biologically inspired and completely artificial muscle driven robot torso that can be fully controlled by a data suit and two five finger data gloves. The underlying biological principles of sensor technology, signal processing, control architecture und actuator technology of our robot platform meet the requirements of biological based technical realization and support a distributed programming and control as well as an online self-adaptation and relearning processing. The following elaboration focuses on biological inspiration for the embodiment of artificial intelligence, gives a short insight into technical realisation of a humanoid robot, which is of high importance in this context, and accentuates highlights relating to a possible paradigm shift in artificial intelligence.

Keywords: embodied artificial intelligence, biological archetype, humanoid robot, biological inspired construction, fluidic muscle, muscle-tendon system, weight saving construction, common platform.

1 Introduction in the Biological Inspiration of the Robot ZAR5

ZARx is a joint project of the Technische Universität Berlin department Bionik und Evolutionstechnik, the company EvoLogics and the company Festo[1].

The aim of this project using the fluidic muscle of Festo [1] is to show the current possibilities of biologically inspired construction in embodiment, muscle-tendon system, control architecture, radius of action, and weight saving.

The robot ZAR5 is a human-like torso with two arms and two five-finger hands which are strictly developed according to bionical considerations. The combination of biology and robotics leads to smoother and compliant movement which is more pleasant for us as people. Biologically inspired robots embody non-rigid movements which are made possible by special joints and actuators that give way and can both actively and passively adapt stiffness in different situations. The more the technical

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realisation corresponds with the biological role model the successful is the reflection of the true reality. If we want to learn more about the control architecture and their functionality in the human being, we have to build an exact copy of the natural role model as much as possible to improve our conceivability of artificial intelligence.

Biological inspiration is not only the morphology – size, proportions and load-bearing inner structures – but also the physiology – moving mechanical parts and muscle tendon systems – as well as parts of the all driven control architecture. The better the morphology is understood and transferred to the artificial body the better the physiological parts can act and thus finally the controlled software. Morphology, physiology and control are an entity and have to be considered always together.

The next two chapters engage with the importance of a biological inspired embodiment for missions in artificial intelligence (AI) and the rest of the paper gives a deeper look in selected issues of the humanoid robot ZAR5.

2 Why Is an Embodiment in AI Necessary?

Intelligence is the Latin word for cognition, perception or comprehension. Based on the natural intelligence of man or animal the essential intelligent criteria can be abstracted to:

- The ability of processing any symbols (not only data),
- The constitution of an inner model of the outer world,
- The ability of an adequate use of the knowledge, and more minor features like
- Reasoning, generalising and specialising.

As archetype of intelligence the human brain is named nearly exclusive. The matter of AI is to understand and reproduce the ability of the human brain in technical applications. Current areas of AI are pattern recognition, speech synthesis/ recognition, programmable machines and expert systems. The fundamental idea of AI is to analyse under which conditions computers can reproduce the behaviour pattern of the intelligence-based creatures.

The intelligence of creatures is evolved by interaction with their environment over millions of years. The peculiarity of the carrier – the embodiment – of the brain has an essential hand in whose development status and intellectual level. The embodiment is the interface between natural intelligence and environment. The complexity or the intellectual height of the brain is determined by the complexity or miscellaneousness of the embodiment. We think always in the complexity of our doing. The more (complex) we can do the more intellectual we are generally.

According to this a detach of an algorithm of AI from their environmentally connecting embodiment leads to an incorrect simulation condition and finally to an insufficient solution by definition.

3 Why an Embodiment Close to a Biological Archetype?

If we accept the above agreement which type of embodiment we should use? That depends on what do you want to do. If we are investigate in special bat skills we have to validate the results on an embodiment which fulfils the requirements of a real bat, concerning the asked features and interfaces. A test on an other mechanical platform seems to be hardly meaningful.

If we test an AI algorithm in the field of muscle control, we have to build an appropriate application which fits the requirements on a muscle-tendon system. The better the respective technical solution meets the underlying methods of the biological role model, the better works the AI algorithm and reflect the real conditions.

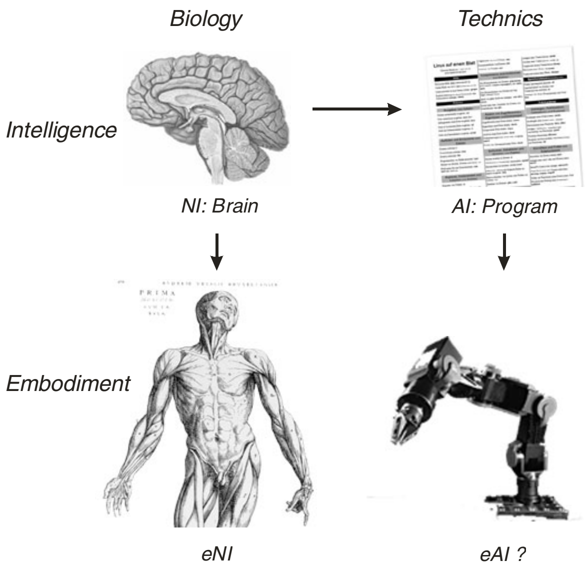

Fig. 1. If the human brain and thinking are archetype to an algorithm or program of AI, how should an appropriate body structure be to prove the functional efficiency?

The possible limits have to be considered depending of what we want to do with our AI algorithm and where shall the algorithm run. Surely we do not want to steer a man but rather reproduce a human skill on a technical application. But if we want to improve a robot with a man's skill, we have to build a human-like robot as far as possible (Fig. 1). Only such an embodiment has the needed requirements to fulfil adequate the posed task.

The AI in terms of a computer algorithm is the technical realisation of the natural intelligence – of the thinking brain. This small piece of reality should be validated gainfully. To come closer to the reality we have to build an embodiment which produces an adequate feedback compared to the archetype. It is not important that the embodiment looks like a man but it is highly important that it copes with the task and the descriptive functionality.

The scientific discipline which deals with the analysis of biological systems and transferring the underlying principles into technical implementations, is called Bionics in German Bionik. Bionics is concerned with decoding 'inventions' made by living organisms and utilising them in innovative engineering techniques. Bionics is a made-up word that links biology and technology. However, nature does not simply supply blueprints which can merely be copied. Findings from functional biology have to be translated into materials and dimensions applicable in practical engineering. It is less the form here but rather the functional coherences which have to translated in a proper way [2].

What can we learn from nature about morphology and physiology for the design of humanoid robots? If we concur with the law of survival of the fittest, then we believe that only optimised individuals can exist in nature in their respective surrounding conditions. Bionics initial task is to search for individuals in nature which have the same characteristics as the object to be developed. In our case, we are searching for a model of a humanoid robot arm and hand. We are thus looking for animals which are able to hold and/or carry several kilograms and which have human-like proportions with respect to weight and inherent compliance. When looking at the problem more closely, the intrinsic problem is how we can produce a multiple of force that is able to hold objects that are heavier than the embodiments own weight. This is the so-called power-weight ratio; this ratio is about one to one for electric motors. We have found other solutions for actuators in nature, particularly linear actuators that produce tractive force. The power-weight ratio of these actuators is multiplicatively higher than those known for technical actuators. Thus, it seems that nature has a better solution for our technical problem under the given terms and conditions.

We will not look at industrial robots here, as they carry out rigid tasks among themselves, or in contact with a technical environment. This field, called contact stability [3-5], has been widely investigated and has presented large problems for robotic manipulation tasks till date.

We will instead focus on human-like robots and their interaction with humans and the environment. This contact or physical touching between robot and human is subject with special requirements regarding softness and compliance of motion [6, 7]. The aim of humanoids is not to assemble printed circuit boards that is also hard for humans, but to master soft and energy-optimised movement in different situations of life.

The question of the appropriate embodiment – morphology and physiology – cannot be answered generally. Certainly it is true that for various questions also a more technical embodiment fulfils the given task. A specific analysis of the question concerning to sensor input, signal processing, actuator output, control loop and interaction with the environment should provide the solution.

Other humanoid robot projects suitable for AI without claim of completeness are e.g. Cog [8], iCub [9], Kismet [10], the Shadow hand [11] or the well-known ASIMO.

4 Humanoid Robot ZAR5 in the Face of the Embodied AI

The current humanoid robot project ZAR5 located in the department *Bionik und Evolutionstechnik* of the *Technische Universität Berlin* is the development and construction of a two-arm robot with two five-finger hands attached to a rigid spinal column (Fig. 2).

Fig. 2. The humanoid robot torso ZAR5 with two arms and two five-finger hands

The whole robot is 190 cm tall, the torso – the upper part of the robot – has a human shape and a weight of about 45 kg and is thus similar to humans of this size. The humanoid robot torso is developed according to a biologically inspired approach as far as possible. Not only the shape, proportions and radii of action but also the deeper and major qualities like skeleton, joints, muscle-tendon systems and data processing of the archetype man are implemented. The company Festo has provided the linear actuators of the fluidic muscles [1]. Tendons of Dyneema® filaments are used to convey the tractive force to the joints regarding tensile strength, lightweight and little bending radius.

The robot ZAR5 can be operated by a batch file, by teach-in and by a data suit and two five-finger data gloves. All joint angles of the data suit wearing man are read and transferred via a main PC located in the base to the controlling microcontrollers and then to the corresponding robot joints. All angular data are read every 20 ms and transferred to the CAN-bus connected microcontrollers of the robot body. This is the path planning stage. Each main body part of the whole robot: right and left hand as well as right and left side of the body is controlled by a system of two microcontrollers. One microcontroller organises the control loops of the connecting joints of this body part and the other one is responsible for the generation of the PWM signals for the fast switching valves. These inner controllers try to follow the given path. Before the tasks are finished they are normally overwritten by the next datagram's from the suit or gloves and thus lead to complex movement trajectories.

The goal of this project in the face of embodied AI is to provide a biologically inspired and manlike platform for the most different algorithms in AI. This platform could get a common interface and base for the latest developments in the algorithmic

AI. The requirements on realistic approach, efficiency, openness, decentralisation and free programmability are fulfilled [12].

The next three chapters give a deeper look in selected issues of the robot ZAR5.

4.1 The Muscle-Tendon System

The study of the physiology of the muscle-tendon system [13-16] of a man and its activation by the central nervous system gives us insight into the functions and activities of the human body. A tendon transmits the tractive power of the human muscle across tissues and special parts of bones. A pair of muscles called 'agonist' and 'antagonist' drives each joint and pulls against each other to build a tonus. All muscles of a joint are located always on the top or proximal side to the centre of rotation. This construction detail leads to less torque and the ability to carry out fast movement with respect to energy need.

The fluidic muscle actuator from Festo [1] is used to meet the requirements on dimensional stability, quantity of shortening and lightweight construction. There are three different types of muscles at the market which output different tensile forces dependent on diameter.

This fluidic muscle actuator works as a linear actuator and shortens in length by an inside pressure above atmospheric. The advantages are a high power-weight ratio, no stick-slip behaviour, works as closed system, no maintenance and no needed retention forces. In the robot application the muscle is used with air pressure of 7 bar. The muscle shortens as an ideal cylinder and is modelled in [17, 18]. The greater the affected force by a constant air pressure is, the smaller is the shortening referred to as base length of the muscle rubber tube. Moreover, the higher the air pressure by a constant force is, the greater is the shortening.

A muscle pair in an antagonistic setup drives each joint of the robot ZAR5 except of the fingers. Tendons of Dyneema® are guided via Bowden cables and pulleys to the joint and transmit the tractive force of the artificial muscle.

The dimensioning of the muscle type, the length and the deflection pulley are the most important tasks in order to fulfil the requirements regarding radius of action, velocity of movement and, in the end, weight to be lifted. Due to being scaled to human proportions, the type and the length of the muscle is limited. The relationship between muscle length and radius of the deflection pulley has been well defined and is calculated beforehand. The smaller the pulley, the smaller the length of the muscle can be, however the muscle have to be more powerful.

Two of the new muscle actuators in combination with an artificial tendon build a completely new actuator system which allows both soft, elastic and compliant as well as force-guided and exact-positioned movements depending on the tonus. This compliance is not actively caused but inherent by the medium air and the material of the muscle, opened the possibility of energy storage and conversion from kinetic energy to potential energy and vice versa and is more pleasant in contact with humans e.g. in the field of assistant robotics. The challenge is the mastering of the nonlinearities and out of it the utilizing of the advantages in the face of energy-optimization, material saving and finally efficiency toward to a more natural movement.

4.2 The Joints

The joints of a humanoid robot are essential for the later capability of its movement shown in different approaches [19-24].

The human shoulder is a ball and socket joint. A technical replica has proven to be a bold venture; this is because the construction involves a group of muscles which covers the shoulder joint and helps to keep the shoulder in the socket and enable the movement of the arm. A surface muscle or the placing of muscles around the joint to imitate the human shoulder muscle-tendon system is awkward to construct and susceptible in operation. A better way to build a complex shoulder joint is to split the multi-freedom joint into separate rotational joints each of which have one degree of freedom. These single joints are easier to construct, can be attached directly to the muscle-tendon system and are more rugged in use. Each of the three rotational joints spans a 2D vector plane around an axis of the Cartesian coordinate system.

The elbow joint – biceps-triceps system – is constructed according to the human system. It is technical a hinge and allows bending and straightening but does not rotate.

The human twist behaviour of the ulna-radius system is a rotary motion of the wrist which can be simplified by a joint with pulley and vertical rotation axis. The challenge of the wrist joint is to duplicate full functionality of the human wrist with a simultaneously simple and durable construction. All tendons of the finger joints have to be concentrated in the middle of the rotation axes. The mechanical resistance in the joint arise from the guidance of the tendons to the sockets of the fingers. In particular, the tilt and lift muscle works against this rising mechanical resistance. For this reason, we have to limit the maximum range of the joint in each direction. Two muscles – flexor und extensor respectively – are used to tilt and lift the joint and are arranged as pairs of antagonists. In the technical sense one speaks of an ellipsoid joint which is a less flexible version of the shoulder's ball-and-socket joint.

The robot's hand has 12 DOF without the wrist. Only the flexor muscle is attached to each finger limb and lays on the extensor as the pullback spring. This construction does not constrict the task of grasping, but only active releasing. This leads to a decrease in size and mass and, due to this, to a smaller inertia of masses and control effort. A disadvantage of this concurrence is the unnecessary additional expenses of providing tractive force via the muscles to overcome the resilience of the springs.

Not only the appearance but rather the function have to be reproduced to build a human-like robot. Thus we have to turn attention to human skills which are determined by the construction of the concerned joints. The better the joints achieve the desired radii of action of man the better the whole robot acts humanoid. Often the archetype of a joint is too complex to reproduce it in detail – we have to do Bionics. This means we reduce the degrees of freedom of e.g. the shoulder joint and separate it in its reference axis. Only by this way we have the chance to control the joint in a proper way. The combined activation of the grounding axis leads to the original capability of movement of the considered joint. The use of simplified joints allow the application of standard bearings and ensure good friction and abrasion properties. More construction details of the joints of our application ZAR5 can be found in [12].

4.3 The Control Architecture

The challenge of the control architecture of an anthropomorphic robot is the design of the electronic components concerning their decentralised tasks and the connecting communication pathways [8, 25-28]. In techniques data cannot really be processed in parallel in opposite to the human brain and the central nervous system of a man. Engineers till date have not been able to reproduce this data flow and communication network in vitro. The task will be to assemble, place and manage electronic parts in the same way as to achieve results similar to that of the human. Many small activities and reactions are not controlled by the brain, but rather initiated by the spinal cord or local reflexes. The advantage of this is shorter reaction time; specialised distributed units can be used as a paradigm to design decentralised control architecture. This approach applied to a technical system is tolerant of failure, enables short distances in the sensor-control-actuator loop and provides a control and command hierarchy.

The robot is divided into four units, completely separately assembled and controlled, one unit for each five-finger hand and one for each arm and shoulder. Each unit has identical circuit devices, functional ranges and consists of two communication directions which can be addressed both separately and independent of each other. All units are connected among each other via CAN-bus. A barebone PC in the base is on the one side connected with the data suit and the two data gloves to read the data of the path planning and on the other side connected to the CAN-bus to address the units and to monitor various values of the whole robot system.

The strict separation of different components and data directions enables speedier troubleshooting and is a first step towards decentralisation. The distribution of responsibilities and the break down of information handling reduces data activities on the bus and the complexity of the units. The fast response time of an unit in a control loop in case of emergency cannot be affected by a fewer crucial task of monitoring or finger play. The remote unit receives a command from the control PC or from another unit via CAN-bus and decides which operations to be done. Without any errors, the unit will initiate the appropriated control loop to reach the demanded goal angle. This stand-alone execution can be interrupted by the control PC or by an exceeded sensor limit value.

The control architecture consists of PC (technical brain), the CAN-bus (technical spinal cord) and the sensory and motor units including controlling electronics (sensory-motor units) is in simple words the connecting system between command (intended action) and action (executive embodiment). The way of doing and extent of the signal transmission from the technical brain to the executive embodiment determine on the one hand the parallelisation, decentralisation and finally the variety of the possible simultaneous and mutually independent movements on the other hand the complexity of the common interface for the users. Actually we have four independently operating units which can be further subdivided in one independent programmable unit per joint in the future. By now the actual software of a unit allows independent quasi-parallel software snippet per joint. We use the CAN-bus layer 2 for the mutual communication of the units [12]. This CAN-bus is also used as a common user interface too. There exists a dedicated interface and protocol description to integrate software parts on top of or into the control architecture to test different algorithms with the humanoid platform ZAR5.

5 Novelty of the Approach and Future Challenges

The used fluidic muscle as a pure pulling actuator seems to be an applicable alternative to the popular electric motor. Through its advantageous properties it is more suitable for humanoid robotics than other drive concepts. The main disadvantage is the use of a second energy form: compressed air. The electric motor obtains the power from the electric current and the fluidic muscle from the attached fluid. The air pipes occupy a bigger volume compared to electric cables but allow the direct quantification of the compliance of each muscle using pressure sensors.

The muscle actuator is suited to locate away from the point of force utilisation. The actuator mass can be easily located in the centre of rotation whereas the produced pulling force is guided via tendons to the point of force taking. Attention has to be turned to the joints which have to house the necessary cables and pipes in its centre of rotation to prevent the forming of loops or kinks during movements. A reduced to the reference axes joint simplifies the measuring of its position and thus the amount of electronic and control effort.

One local electronic control unit per joint allows not only the management of the connecting sensor data, signal processing, control and actuator triggering but also the implementation of special local functions like reflexes, online learning strategies and exception handlings. Local functions are joint dependent, preferably not interruptible from the higher levels, independent of the path planning and thus applicable to real-time use.

A proper control architecture connects all lower level units and achieves the higher level path planning from the main controller in our application an usual personal computer.

The next steps in the development process of the humanoid robot project ZAR5 are to divide the actual four units into one smaller and low-end unit for each joint for basal functions, to provide the possibility of changing and updating the software code of all CAN-bus connected units, to implement higher and lower level learning strategies and to make the sensor technology and the cable connection points more robust.

Learning strategies enable the optimisation of control parameters or the whole control structures during operation. An individual joint or a chain of joints can adapt its parameters depending on different requirements like overshoot, transient response or simply the speed of movement. Depending on the priority of the measured values, that have to be processed, the optimising algorithms can be located on the different control levels. The main processor – the brain – is responsible for holding, up-to-dateness, replacement and finally management of the different kinds of learning mechanisms.

Such kind of open platform is always limited by the used components both hardware and software. Are they designed too open no common rules and interfaces emerge. Are limited to few features it does not meet the complexity of the real situation. A reasonable platform has to be restricted as possible and extensive as necessary.

6 Conclusion

An adequate embodiment as reasonable interface to the environmental condition seems to be necessary for a testbed of an AI algorithm. A method, which links together software and a physical object, is only as good as the flimsiest element. The better the used embodiment represents the reality the better the expected solution for a characterised task in AI will be. Each task may require its own particular embodiment. An AI algorithm for the reproduction of a human motion pattern and reflex demands an anthropomorphic representation of at least one joint of a man. The respective embodiment has absolutely not look like a man but must reproduce the essential requirements on structure and function. The underlying principles of the biological archetype have to be implemented.

With the briefly introduced anthropomorphic and man-like torso a worldwide leadoff platform can emerge which facilitates a common working and testing under same conditions. Repeated tasks are prevented and the solutions are comparable among each other.

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