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Design and Kinematics of a Biologically-Inspired Leg for a Six-Legged Walking Machine

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***Abstract*— Legged locomotion is a fascinating form of motion. Almost all legged robotic systems are biologically-inspired by some kind of role model. The stick insect and cockroach are two of the most popular role models in the field of six-legged walking robots. Although, their legs have at least four degrees of freedom, most robotic systems, which are biologically-inspired by these insects, come along with only three joints in each leg. In this paper we will present a new leg design with four degrees of freedom for the six-legged walking machine LAURON. This enlarges the workspace of our leg significantly compared to previous leg generations and makes it very similar to the leg of the stick insect. With the additional rotational fourth joint the kinematic structure becomes redundant. The inverse kinematics for this redundant structure is solved in a very efficient way by benefiting from the orientational redundancy.**

***Index Terms*— six-legged walking machine, hexapod, design, kinematics, stick insect**

I. INTRODUCTION

During millions of years, evolution has created very fascinating ways of moving through all sorts of environments. Walking, running and jumping are some of the most interesting forms of terrestrial locomotion. Many animals and insects have brought their form of locomotion near to perfection, like the astonishingly fast cockroach or the great climbing gecko. Scientists and engineers have been observing animal locomotion for hundreds of years and are still fascinated and trying to reveal nature's secrets all over the world. Consequently, developers of legged robotic systems try to imitate nature's impressive construction and coordination principles. Today, one can find biologically-inspired robotic systems in almost all fields of robotic research.

For example, Robert Wood has developed an insect-sized aerial robot [1], which is able to lift-off all by itself. Then, other authors like Kuehn et al. are developing ape-like robots, which are biologically-inspired by a chimpanzee [2]. The lengths of body segments are proportional to those found in chimpanzees. But, not only the mechanical structure, also the walking pattern generation is strongly related to an ape. Other biologically-inspired robotic systems can operate on land and in water, like the amphibious snake-like robot ACM-R5 [3].

Despite many technical achievements, legged locomotion, as it can be found in many different forms in nature and is performed so easily by us, still remains to be a big technical challenge. This challenge is addressed in many different ways, leading to the big variety of legged robotic systems.

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The impressive quadruped robots from Boston Dynamics *Big Dog* and *Little Dog* are well known examples for biologically-inspired robotic systems. Other legged robots, like ANTON from the University of Magdeburg in Germany were inspired by an ant [4]. Its kinematic structure is very close to its biological role model. Daniel Kingsley and his colleagues have developed a cockroach-like robot, which is not actuated by motors, but by artificial muscles [5].

Most six-legged walking robots have legs with three joints, although biological role models, like the cockroach, ant or stick insect, usually have at least four joints in each leg.

In this article we will present a biologically-inspired design of a leg with four joints for a six-legged walking robot. The presented leg construction is based on a previous leg design with three joints, as it is realised in the walking machine LAURON IVc (see Fig. 4) and the biological leg design of the stick insect. With the additional rotational joint the workspace is significantly enlarged. Therefore, this fourth degree of freedom offers interesting new kinematic possibilities, which will be studied in the future. The extra joint in the new design adds a minimum of mass, while maintaining the high robustness of the former leg design. Different mechanical designs are evaluated in this paper leading to a final design. The redundant kinematic structure offers great potential for new types of locomotion, but also comes with the drawback of undetermined inverse kinematics. This problem is solved by introducing an additional kinematic constraint to the leg kinematics. In this manner, it is possible to overcome the problems of the inverse kinematics with a closed geometrical solution.

During the following section II, we will present the chronological development of the LAURON walking machine. This development and the study of the biological role model, the stick insect, have lead to the new leg design, which is then described in section III. In the section IV we will give some details on the kinematics of the new design. Finally, we will summarise this work and present some future work in section V.

II. DESIGN AND DEVELOPMENT OF LAURON

The walking robot LAURON was first developed at the FZI Research Centre for Information Technology, Karlsruhe Germany, as a test platform for machine learning. Later it was mainly used to study six-legged locomotion in rough terrain. Today, the focus still lies on locomotion, but also on topics like self-localisation, navigation and mission planning.

In the early 90s several prototypes were developed with the objective to find the best geometry for the leg of a

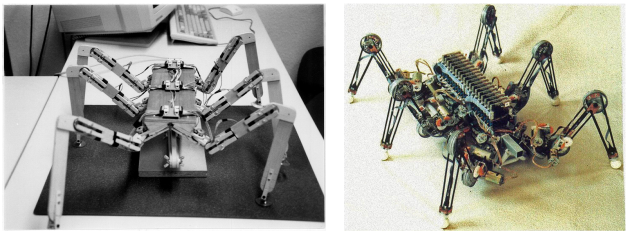

Fig. 1. (left) INSECT (1992): First wooden prototype with joint sensors, but no actuators, (right) LAURON I (1994): **L**egged **Au**tonomous **Ro**bot **N**eural Controlled.

six-legged walking machine. A first wooden prototype with three joints had no motors, but was able to measure its joint angles with potentiometers. In 1992 the construction of a six-legged wooden prototype was finished [6]. This model was called INSECT (see left side of Fig. 1). Similar to the first leg prototype, it was not equipped with any actuators and therefore could not move by itself. The three joint angles were still measured with the help of potentiometers. Hence, it was possible to record and analyse leg trajectories.

After a fully functional wooden leg, with dc motors and high precision optical joint encoders had been developed, the first LAURON robot was built (see right side of Fig. 1). This robot was then presented to the public at the CEBIT 1994. When standing on the ground LAURON had a contact area of approximately 0.5 x 0.6 m. In order to reduce its weight, most of the parts were made of fibre-reinforced plastics. With all its components LAURON had a weight of 11 kg. The six identical legs were attached to a rigid main body, an aluminium square pipe, in a downwards angle of 30 degrees [6]. Besides, the front and rear legs were additionally rotated by an angle of 30 degrees around the centre of the main body. The entire construction of LAURON was biologically-inspired by the stick insect Carausius Morosus. The sizes of the leg elements have a similar ratio as the legs of the stick insect. Compared to the stick insect, the coxa joint δ and the tarsus were not realised in this first design of LAURON (see Fig. 5). The robot was controlled by neural

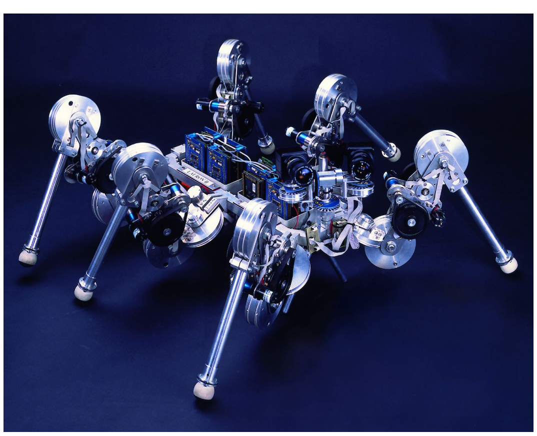

Fig. 2. LAURON II (1994): Improved Mechanics with aluminium legs and new stereo-camera head.

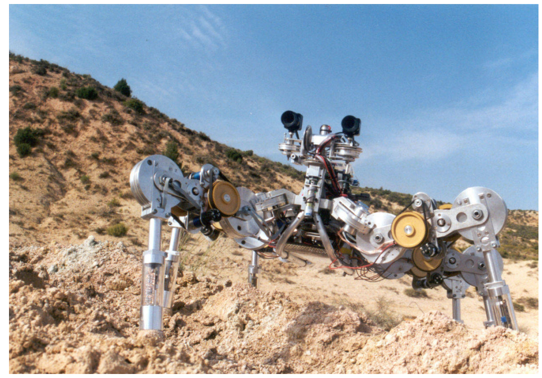

Fig. 3. LAURON III (1999): Equipped with a hierarchical reactive control system and research focus on new topics like localisation and navigation.

networks, which is represented by the "N" in LAURON's name (**L**egged **Au**tonmous **Ro**bot **N**eural Controlled).

At the end of 1994 the next robot generation, LAURON II (shown in Fig. 2), was developed. This walking machine was a mechanically improved advancement of LAURON I. The six identical legs were now made of lightweight aluminium and fixed to a constructive frame. Of course, this and the increased size has led to a higher weight of approx. 16 kg. LAURON II had a ground contact area of 0.7 x 0.7 m and was equipped with several new sensors, for example a stereo-camera head at the front of the robot. This walking robot was used to test and evaluate different control strategies. Most of these strategies were based on machine learning methods like supervised and unsupervised learning or closed-loop algorithms like fuzzy-controllers or active compliance controllers [7].

In the year 1999 LAURON III was constructed (shown in Fig. 3). This robot was the result of technical advancements applied to LAURON II. The size was kept at 0.7 x 0.7 m when standing on the ground, but the weight increased to 18 kg. LAURON III was able to carry a payload of approx. 10 kg. This robot was no longer controlled by a neural network, instead it was controlled by a hierarchical modular reactive control system [8]. During the years of development, the research focus shifted from the walking process to new fields, e.g. localisation, navigation and environment modelling [9].

Fig. 4 shows the fourth generation of LAURON, which was developed in the year 2004. Like its ancestors, LAURON IV was still biologically-inspired by the stick insect Carausius Morosus. The mechanical construction was re-designed, with the target to increase robustness. The six identical legs, which are now using gear belts instead of round cord belts, are attached to a main carbon fibre body. A new head with two degrees of freedom was placed on the front end of its body. LAURON IV is bigger than LAURON III and reaches a size of approx. 1.2 x 1.0 m, when standing on the ground. Therefore, its weight has also increased to about 27kg. It can carry an experimentally proven payload of up to 15kg. Other experiments have shown that it can reach a maximum speed of 0.22 m/s. Inside the carbon fibre

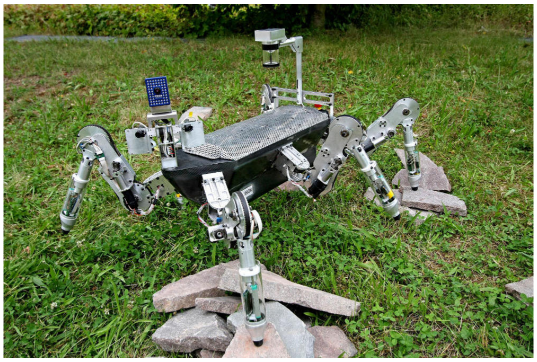

Fig. 4. LAURON IVc (2005): Latest generation of LAURON with a main carbon fibre body, equipped with many high level sensor systems like the time-of-flight camera.

body, LAURON IV is equipped with two embedded PC-104 systems, low-level control hardware and NiMH cells, which can power the entire robot for approximately 60 minutes. From one generation to the other, LAURON has always been equipped with more and more sensor systems. Important sensor systems on LAURON IV are the three camera systems (stereo-camera, omni-directional camera, time-of-flight camera), an inertial sensor system and a GPS sensor. Of course, LAURON IV can also detect leg collisions and its ground contact with the help of its 3D foot force sensors, spring force sensors and motor current sensors. The latest version of the fourth generation is LAURON IVc. It was completed at the end of the year 2005. Some smaller mechanical improvements in the legs and new low-level control hardware distinguish the first and latest version of LAURON IV.

III. DESIGN OF A NEW LEG

Although LAURON IVc is able to easily walk over very rough and unstructured terrain, it is not able to walk up walls or climb in the branches of a tree, like its biological role model, the stick insect. The stick insect has four joints in each leg. Eltze has observed that the stick insect only uses the coxa joint δ while climbing [10]. If the stick insect is walking on a plane, this joint is not used. Probably this is a reason why so many six-legged robots come along with only three joints.

The new leg was designed with the ambition to reduce the gap between the capabilities of the stick insect and LAURON. By introducing a fourth joint in each leg, similar to the coxa joint δ of the stick insect (see Fig. 5), the workspace of each leg is increased dramatically. For example, the foot can now be orientated in a desired angle to the ground. The next LAURON generation will be able to use this increased workspace to walk and climb over more complex and difficult obstacles, e.g. steep stairs.

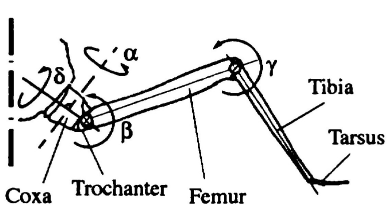

Fig. 5. Leg of a stick insect with four joints [10]. Joint names α, β, γ and δ are identical to those used in the LAURON leg design.

A. *Different Mechanical Joint Designs*

The biggest challenge was to add this additional joint and to still fulfil the conflicting constraints, e.g. a minimum of weight and a maximum of torque, angular velocity and robustness. The first three joints δ, α and β could also be realised as one ball-and-socket joint. But the technical problem to actuate such a joint has led to the decision to use three independent joints instead. Different possible solutions for the additional rotational joint δ have been evaluated. This section will shortly describe these concepts and their assets and drawbacks.

- A concept based on a spur wheel section could be realised in a very small and compact way. A disadvantage is that the next joint (α) has to be placed more outwards, making the robot wider.
- A ring gear could be attached to the main body. Then the second joint (α) could be integrated in the inner part of this ring gear. Advantages of this concept are a reduced backlash compared to a concept with a spur wheel section and the good load transmission due to higher number of teeth. But this concept would require a very complex bearing.
- The rotational joint could also be realised with the help of a worm gear. Besides the positive self-locking characteristic this concept would need a lot of space and its efficiency would be inferior compared to the other concepts.
- The usage of a harmonic drive could have some big advantages. On the one side, it is possible to realise very high gear transmission ratios. On the other side harmonic drives have nearly no backlash and can be integrated in very compact ways. However, harmonic drives are very expensive compared to other gear types.
- A concept which only employs one motor could have the advantage of being very lightweight. The DC motor is one of the heaviest parts in the leg. But this would also mean that only one joint can be moved at the time and that some sort of clutch would be required.

Although, the harmonic drive is probably the technically best solution, the spur wheel section concept has been chosen. It can be realised in a very compact way by using the inner space for the second joint α. In this way the two motors can be placed very close to each other, which minimises the necessary space. Besides, the spur wheel section is similar to the bevel gears used in the other joints of the leg and therefore leads to a homogeneous design. The small drawback of moving second joint (α) outwards can be addressed when constructing the main body. The higher

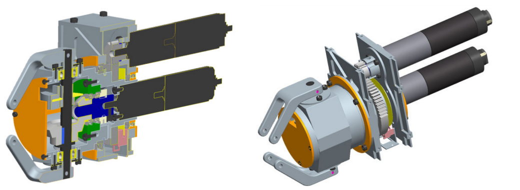

Fig. 6. CAD Construction of the spur wheel section concept.

costs of a harmonic drive are also an important argument for the spur wheel concept.

B. Design of the Additional Joint

The motors, bearings and other important mechanical parts have a great influence on the final design of the additional joint. The dc motors are a key part in such an assembly. Many different motors have been considered for the new leg design. The “Faulhaber dc motors”, already used in LAURON IV, feature the best trade-off between weight, maximum torque and angular velocity. Therefore, all joints, including the new rotational joint, will be equipped with this kind of dc motor. After estimating the maximum theoretical forces and torques, which will stress the α and δ joints, it was possible to select the required bearing and gearing. The final design of the new rotational joint δ together with the adapted joint α can be seen as CAD construction in Fig. 6.

C. Design of the Walking Machine Leg

After having finished the design of the new δ and α joint, the rest of the leg can be constructed. The leg design of LAURON IV has proved to be very robust and reliable. Hence, the design of the rest of the leg will be derived from this former design. The aluminium square profile connecting the β and γ joint is modified, resulting in a bigger angular range for these joints. Other smaller adaptations improve the serviceability.

All four joints are integrated into the final leg design. The CAD construction of this leg is presented in the left part of Fig. 7. Of course, this new design with its additional joint is heavier than the former design. The weight of one new leg has increased to 3.9 kg. A first prototype of this leg (see right part of Fig. 7) has already been assembled and several experiments have been performed in order to test and stress the new construction. These tests have shown that the new leg design is able to fulfil the requirements of the next LAURON generation. The measured angular velocities are at reasonably high values (δ: 85.71 deg/s, α: 116.88 deg/s, β and γ: 112.5 deg/s) and the leg was able to resist a force of 240 N. Therefore, the leg is fast, very robust and already two legs can easily carry the approx. weight of the next LAURON generation.

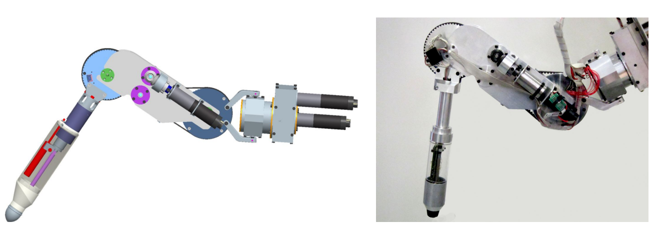

Fig. 7. (left) CAD construction of the new LAURON leg, (right) Picture of the new LAURON leg.

TABLE I
DH-PARAMETERS OF THE NEW LAURON LEG

joint q_i	θ_i (m)	d_i (m)	a_i	α_i (rad)
q_1	δ	0.032	0	$\frac{\pi}{2}$
q_2	α	0	0.089	$\frac{\pi}{2}$
q_3	β	0	0.2	0
q_4	γ	0	0.324	0

IV. KINEMATICS

A. Direct Kinematics

The direct kinematics of the new LAURON leg is calculated based on the Denavit-Hartenberg-Parameters. In this section the joints are renamed for an easier equation handling and because of the conflicting names when working with the Denavit-Hartenberg convention. The α, β and γ joints are now described as joints q_2, q_3 and q_4. The new additional rotational joint δ is now q_1. When choosing the frames according to the Denavit-Hartenberg convention (see Fig. 8), it is possible to calculate the direct kinematics with the homogeneous transformation $\underline{A}_{i+1}^{i}$:

$$\underline{A}_{i+1}^{i} = \begin{pmatrix} \cos q_i & -\sin q_i \cos\alpha_i & \sin\theta_i \sin\alpha_i & a_i \cos\theta_i \\ \sin q_i & \cos q_i \cos\alpha_i & -\cos\theta_i \sin\alpha_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$

Together with the DH-Parameters shown in Table I the direct kinematics from the first joint q_1 to the foot point can easily be solved. Because the multiplication of four homogeneous transformation matrices can be performed very quickly, the direct kinematics problem can be considered as solved.

B. Inverse Kinematics

Unfortunately, the inverse kinematics problem is considerably more difficult to solve. Many foot tip positions can be reached with multiple joint configurations; hence, the inverse kinematic is ambiguous. This redundant kinematic structure of the new leg leads to mathematical problems when trying to solve the inverse kinematics.

In general, the inverse kinematics problem can be solved geometrically, algebraically or with numeric analysis. In this work the inverse kinematics problem is solved geometrically, with the target to create an efficient solution. The hybrid control system of this new leg (force and position [11]), which is not in the scope of this paper, requires a computationally quick solution. The problem of the redundant kinematic structure is solved by defining an additional kinematic constraint [11]. The orientation of the foot relative to the ground can be seen as an abstract degree of freedom. By

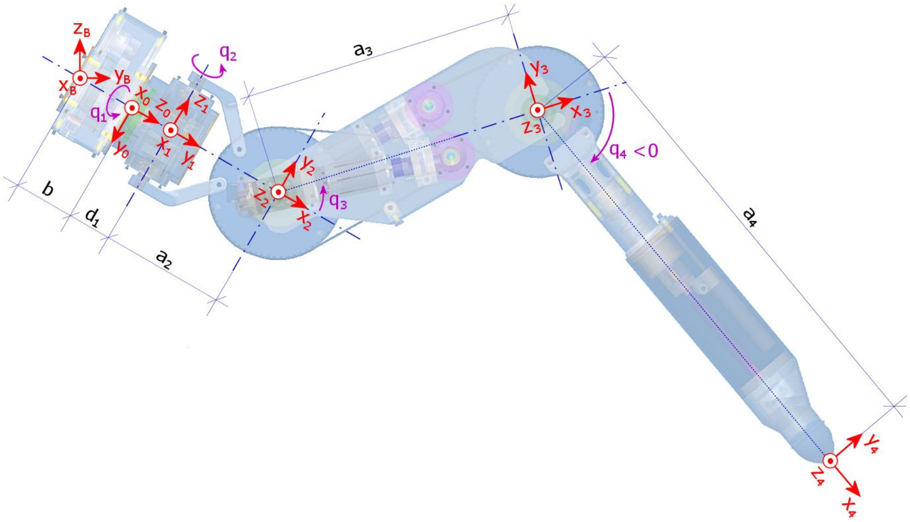

Fig. 8. Leg frames according to Denavit-Hartenberg convention: red coordinate systems show the frame$_B$, frame$_0$, frame$_1$, frame$_2$, frame$_3$, frame$_4$.

orientating the leg towards the ground in a certain angle, it is possible to influence the load transmission to the ground and reduce the mechanical stress.

The geometrical inverse kinematics problem was divided into an orientation and positioning part.

Orientation

Because, all parts of the new leg are situated in the same plane starting from joint q_2, it is possible to express the position vector of the foot tip in the frame$_1$ (refer to Fig. 8). This transformation is realised with

$$\underline{p}_{d14} = (\underline{A}_1^0)^{-1} \underline{p}_d \quad \text{with} \quad \underline{p}_d = \begin{pmatrix} p_{dx} \\ p_{dy} \\ p_{dz} \end{pmatrix},$$

resulting in

$$\underline{p}_{d14} = \begin{pmatrix} p_{d14x} \\ p_{d14y} \\ p_{d14z} \end{pmatrix} = \begin{pmatrix} \sin(q_1)\, p_{dy} + p_{dx} \cos(q_1) \\ p_{dz} - d_1 \\ \sin(q_1)\, p_{dx} - \cos(q_1)\, p_{dy} \end{pmatrix},$$

where $\underline{p}_d$ is the desired foot tip position in frame$_0$.

Figure 9 shows the geometrical relations between the position vector of the foot tip and the frame$_1$. These relations lead to the first orientation equation:

$$\begin{aligned} q_2 &= atan2(p_{d14y}, p_{d14x}) \\ &= atan2\left(p_{dz} - d_1, \sin(q_1)\, p_{dy} + p_{dx} \cos(q_1)\right). \end{aligned}$$

With the additional kinematic assumption of orientating the z-axis of frame$_4$ parallel to the x_B-y_B-plane (see Fig. 8). The kinematic assumption creates the second orientation equation:

$$-1/2\sqrt{3}\sin(q_1)\sin(q_2) + 1/2\cos(q_2) = 0$$

Finally, the orientation part of the inverse kinematic problems ends with a solution of this system of equations. The equations for the joints q_1 and q_2 are:

$$q_1 = \arcsin\left(1/3\,\frac{p_{d14x}\sqrt{3}}{p_{d14y}}\right)$$

$$q_2 = \arctan\left(p_{d14y}, p_{d14x}\right).$$

Positioning

Fig. 10 shows us the geometrical relations between the different leg parts in the x_2-y_2-plane. Now, the position vector of the foot tip has to be expressed in frame$_2$:

$$\begin{pmatrix} p_{d24x} \\ p_{d24y} \\ p_{d24z} \end{pmatrix} = \begin{pmatrix} p_{dx}c_2c_1 + s_1 p_{dy} c_2 + s_2 p_{dz} - s_2 d_1 - a_2 \\ s_1 p_{dx} - c_1 p_{dy} \\ s_2 p_{dx} c_1 + s_1 s_2 p_{dy} - c_2 p_{dz} + d_1 c_2 \end{pmatrix}.$$

In the last equations the functions sin() and cos() were replaced by the symbols s and c. The indices of these

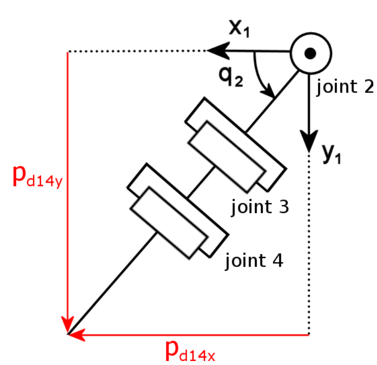

Fig. 9. Derivation of the geometrical relations needed for the orientation equation.

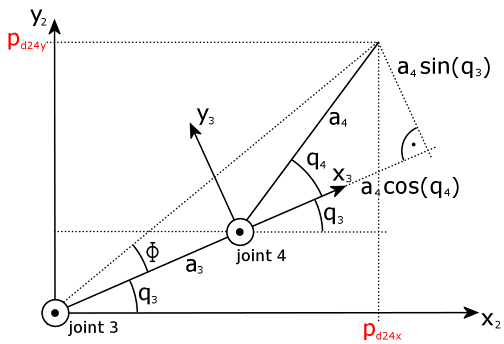

Fig. 10. Illustration of the positioning problem in the x_2-y_2-plane.

symbols correspond to the angle q_i of the joint i. The elements p_{d24x} and p_{d24y} can be used to form the expression

$$p_{d24x}^2 + p_{d24y}^2 = a_3^2 + 2a_3a_4\cos(q_4) + a_4^2.$$

Solving this expression leads to the equation for q_4. The last equation for joint q_3 can be found by introducing the angle Φ (see Fig. 10). The two geometrical relations

$$\tan(\Phi + q_3) = \frac{p_{d24y}}{p_{d24x}} = \frac{\tan(\Phi) + \tan(q_3)}{1 - \tan(\Phi)\tan(q_3)}$$

and

$$\tan(\Phi) = \frac{a_4^2 \sin(q_4)}{a_3 + a_4\cos(q_4)}$$

can then be used to find the solution for q_3.

At the end of the positioning part we have the equations for the last two joints q_3 and q_4:

$$q_3 = atan(\frac{p_{d24y}a_3 + p_{d24y}a_4\cos(q_4) - p_{d24x}a_4\sin(q_4)}{p_{d24x}a_3 + p_{d24x}a_4\cos(q_4) - p_{d24y}a_4\sin(q_4)})$$

$$q_4 = -\arccos(\frac{1}{2}\frac{p_{d24x}^2 + p_{d24y}^2 - a_3^2 - a_4^2}{a_3a_4}).$$

Finally, we have a closed geometrical solution for the inverse kinematics problem. This solution only uses trigonometric functions and can be considered as rather simple. It is possible to calculate the inverse kinematics quick enough in order to use the solutions and feed them to the control system.

V. CONCLUSION AND FUTURE WORK

A. Conclusion

In this paper we have presented the chronological development of the walking machine LAURON. This development has led to the presented leg design, which was biologically-inspired by the four joints of the stick insect and the former leg design of LAURON IV. The workspace of the new leg is considerably larger and this enables us to move along interesting new kinds of leg trajectories. It will extend the walking and climbing capabilities of the next LAURON generation. The drawback of this redundant kinematic structure is its ambiguity. But, this problem has been solved in a very efficient way, by actively controlling the angle of the foot tip relative to the ground.

B. Future Work

In the near future we are going to test the presented leg design on the next generation of LAURON. This new leg construction will enable us to walk with new locomotion strategies, walking patterns and climb over more complex obstacles. Theoretically, we will be able to walk in a mammal like way with this new leg design. The additional joint enables us to orientate the foot tip towards the ground in a controlled way. Hence, LAURON V will be able to control its impact on the ground and use this advantage to reduce its leg slippage, enabling faster and energy-efficient locomotion. Our goal for the future is to reduce the gap between the walking capabilities of a stick insect and our walking machine LAURON.

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