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# Kinematic study of the spider system in a biomimetic perspective

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***Abstract*— The spiders' ability of walking and climbing on different surfaces and in different conditions is taken into account in this paper in order to define and study a suitable spider-model for a future climbing-robot prototype that can autonomously explore dangerous and extra-terrestrial surfaces. Indeed, the spider shows all of the requisites for the exploration in these non-structured environments: low mass, high motion capabilities, climbing abilities and embedded decision elements. In order to understand how the spiders can walk and climb, the attaching mechanisms, the dynamics of the adhesion and the legs' movements are evaluated. Thanks to this approach structural and dynamic directives for the model are found and the mobility of the real spider can be studied in order to define a suitable bio-mimetic model.**

**The found simplified model is analyzed from a kinematic point of view considering the different conditions of contact and flight for the eight available legs.**

**A kinematic simulator that controls the overall degree of adhesion of the system and the locomotion pattern of the developed spider model is implemented to confirm the effectiveness of the choices.**

## I. INTRODUCTION

In recent decades, the progress in manufacturing automation and robotics allowed to think to replace the humans in dangerous, inaccessible working environments.

Nanotechnology and microrobotics offered the possibility of creating autonomous miniaturized structures used for a wide range of tasks, like the use of robots in securing land-mined areas, inspection of large mechanical structures that present hazard (e.g. electric poles), exploration of narrow and inaccessible environments like underwater structures, industrial pipes or outer-space exploration. Exploration in non-structured environments requires low mass, versatility, climbing abilities and embedded decision elements. Two of the most important requirements to satisfy, in order to develop such devices, are the autonomous working capacity without any linkage to a mother-structure, and very low energy consumption.

Different types of locomotion have been attempted in order to allow all-surface locomotion, but some of the methods, like air-suction and electromagnets [1], [2], [3], presented the disadvantage of very limited autonomy because of the power supplies needed in order to work, along with the limitations introduced by the surfaces that these mechanical structures should climb. Moreover the problems due to the lack of atmosphere in space applications have to be taken into account. So the attention turned to biological creatures able to climb fast and run over various types of surfaces in unstructured environments and in different weather conditions. Replicating these creatures, like spiders, lizards or insects is no easy task because the locomotion techniques used are not fully understood and more advanced research using modern measuring and observation equipments is required.

In this paper the attention is turned on spiders. These arachnids are capable to efficiently operate and nimbly move in unstructured environments. Spiders can climb on vertical surfaces, upside-down, easily overcome obstacles thanks to the mobility of their legs (not possible in other well studied insects like cockroaches and geckos), build webs and can also walk on them.

Several engineering prototypes of legged systems have been developed but they are mainly based on macroscopic observations of the animal's design and do not take into account the climbing abilities of the real system.

In order to define a suitable model, the biological system and the climbing abilities of the spider have to be evaluated.

## II. THE SPIDER

The spiders and other arachnids have only two major body parts. The anterior part is called the cephalothorax or prosoma, and the posterior part is called abdomen, or opisthosoma. Spiders have eight legs attached to the cephalothorax and each leg is composed of seven segments [4]. In order to be able to climb various surfaces the spiders use two types of different attaching mechanisms: the claws and the hairs.

The claws are used for locomotion, during climbing rough hard surfaces (stone) or soft surfaces (tree bark, leaves), and web building, in order to spin the silk threads or walk on the already built web. Considering the micro-nano hairs on the spider limbs, they allow the spider to attach to a several different kind of surfaces thanks to the intermolecular attraction forces between the spider's hairs and the climbing surface (tree bark, rock, stucco, metal, glass or plastics). Due to these two different attaching mechanisms, such amazing animals are able to cling to almost all the surfaces.

The jumping spider *Evarcha arcuata* can walk, climb over and jump between different types of surfaces. In [5], [6] it has been studied and observed from a biological perspective. Like in other spiders, the tarsus of all the eight feet of the *E. arcuata* is both covered with hierarchic setal structures used for adhesion on any type of surfaces, and provided with two claws for rough surfaces. The setal structures of *E. arcuata* are a ramified hierarchical structure. The tip of the tarsus of each leg is covered with the *setae*, a relatively long thin hairs,

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that split and branch at their end into the so called *setulae*. Each of these *setulae* has a flattened tip called *spatula* that allows to maximize the contact area with the substrate. From the Atomic Force Measurement (AFM) analysis it results that a single *setula* creates an attachment force of $38.12nN$, leading to a total adhesive force of $2.38 \cdot 10^{-2}N$. The spider *E. arcuata* can produce an adhesion force to sustain 160 times its body weight and be able to climb the substrates in any condition and in safety.

The dynamic of the attaching and detaching movements has to be evaluated and studied in order to mimic the abilities of the spider locomotion and adhesion. First, observation of other biological systems shows that the adhesion increases when not only a normal load, but also a parallel load is applied [7], [8]. Hence, it is possible to argue that in spiders, as demonstrated for geckos [7], in order to establish an intimate contact between the attaching elements and the surface, not only a normal preload but also a parallel sliding movement is necessary. Moreover, looking to the approaching behavior in the attaching and detaching phases, an angle and a succession of movements that enhance the adhesion and allow to attach and detach rapidly the spiders' feet can be found. By studying a finite element model of a *seta*, Gao [9] defined two mechanisms of adhesion failure depending on the pulling angle: sliding off ($< 30^o$) and detachment ($> 30^o$). When a $30^o$ condition between the adhesive beams and the substrate is reached, the maximum adhesion force is achieved. This suggests that a suitable increasing of the setal angle from $30^o$ allows to rapidly detach the *setae* from the substrate.

In a bio-mimetic robotic approach both the above remarks have to be taken into account in order to control the angle of adhesion and the proximal and distal movements of the prototype's legs. Considering that the spiders as the *E. arcuata* have the attaching mechanisms on the tip of the tarsus limbs, the considerations made about the correct angle of adhesion of the setal structure can be extended to the last limb of the leg's chain.

An accurate control of the approaching angle between the last limb of the leg and the substrate can bring to a correct implementation of the adhesion and detachment phases.

A definition of a correct spider-model requires a kinematic analysis of the real arachnid systems.

## III. Mobility analysis of spider's legs

The spider's leg has seven limbs: coxa, trochanter, femur, patella, tibia, metatarsus and tarsus. In Fig. 1,2 the leg with the found angles of motion is shown.

Coxa is the first limb between the body and other limbs. As there are seven limbs in the leg of a spider, there are seven joints to be examined. It has been assumed that the joints of various spider species are the same and these are of two types: monocondylar and bicondylar. Looking at the analysis made in [4], [10], [11], [12], [13], [14], [15], that investigate the possible movements and rotations of each joint, the joints can be evaluated from a mechanical point of view:

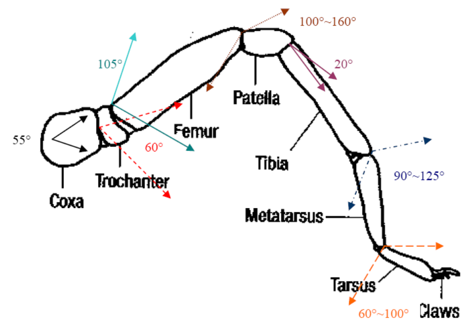


Fig. 1. Ranges of motion for joints in Y-Z plane (based on Foelix's results [4])

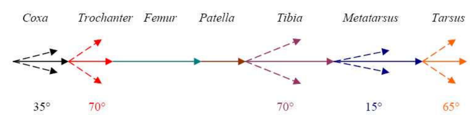


Fig. 2. Ranges of motion for joints in X-Y plane (based on Foelix's results [4])

1) *Body-Coxa joint*: this joint can be viewed as a three degrees of freedom (DOFs) ball-and-socket joint;
2) *Coxa-Trochanter joint*: there are two different views about this joint, either a 3-DOFs ball-and-socket or a 2-DOFs saddle joint.
3) *Trochanter-Femur joint*: this joint can be modeled as a universal joint with 2-DOFs;
4) *Femur-Patella joint*: this joint can be modeled as a hinge joint;
5) *Patella-Tibia joint*: it is possible to model this joint as a hinge joint, or a universal joint with very limited joint on Y-Z axis;
6) *Tibia-Metatarsus joint*: it is also possible to assume this joint as a hinge joint, or a universal joint with very limited motion on X-Y axis, in contrast with patella-tibia joint;
7) *Metatarsus-Tarsus joint*: this joint can be modeled as a universal joint.

The mobility of all the joints and the degrees of freedom per leg depend on the position and condition of each leg. In the free flight configuration (i.e. leg not in contact with the substrate), the spider's leg can be viewed as a 7-joint manipulator while, in the contact condition (i.e. leg in contact with the surface), an equivalent additional spherical joint must be considered.

In order to carry out a mobility analysis of the spider system, the mobility equation (Kutzback equation) is employed:

$$d = 6 \cdot (n-1) - \sum_{i=1}^{j} (6 - f_i)$$

where $n$ is the number of links, $j$ the number of joints, $f_i$ the number of DOFs per every joint and $d$ = number of DOFs per leg. Then, computing the mobility in the two different cases, in the free flight case the DOFs result $d = 14$ and in the contact case $d = 17$. In Tab.I the mobility analysis results as a function of the number of legs in contact (g) and the number of DOFs per leg (d) are shown. When

TABLE I
MOBILITY OF THE SPIDER SYSTEM.

| d | g | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 3 | 3 | 0 | -3 | -6 | -9 | -12 | -15 | -18 |
| 4 | 4 | 2 | 0 | -2 | -4 | -6 | -8 | -10 |
| 5 | 5 | 4 | 3 | 2 | 1 | 0 | -1 | -2 |
| 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 7 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 8 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 |
| 9 | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 |
| 10 | 10 | 14 | 18 | 22 | 26 | 30 | 34 | 38 |
| 11 | 11 | 16 | 21 | 26 | 31 | 36 | 41 | 46 |
| 12 | 12 | 18 | 24 | 30 | 36 | 42 | 48 | 54 |
| 13 | 13 | 20 | 27 | 34 | 41 | 48 | 55 | 62 |
| 14 | 14 | 22 | 30 | 38 | 46 | 54 | 62 | 70 |
| 15 | 15 | 24 | 33 | 42 | 51 | 60 | 69 | 78 |
| 16 | 16 | 26 | 36 | 46 | 56 | 66 | 76 | 86 |
| 17 | 17 | 28 | 39 | 50 | 61 | 72 | 83 | 94 |

$d > 6$, an increase of $g$ brings to an augmentation of the overall mobility of the system. If $d < 6$ an increase of $g$ brings to a reduction of the overall mobility of the system. When $d = 6$ the mobility of the system is always 6 in spite of the number of legs in contact with the surface.
Looking at the mobility of the real spider it is possible to underline that the system has 94 DOFs when 8 legs are in contact with the surface and 50 DOFs when 4 legs are in contact with the surface. These results are justified by the fact that the spider's legs are used not only for walking but also for manipulating objects, capturing prey and sensing the environment. Due to these considerations, a reduction of the complexity of the system, that for now is unimaginable to mimic in a bio-robotic perspective, has to be made.
The robotic system has to allow the control of the body system and, consequently, must have at least 6 DOFs (3 positions, 3 rotations). The number of DOFs per leg has to be $d \geq 6$ but as small as possible, in order to be feasible.
In the previous analysis it emerged that for controlling the adhesion of every leg the approaching angle must be suitably controlled. Then, at least one extra degree of freedom per leg has to be available in order to define and control the approaching angle between the tarsus link and the substrate. Thus, in the following kinematic model the DOFs per leg are set to 7.

## IV. KINEMATIC MODEL OF THE SPIDER'S LEG

The simplified model of the spider, chosen according to the previous analysis, is an eight legged structure with a round body plate; the number of legs of the spider creates indeed a good compromise between the stability and the complexity. The legs are radially collocated with respect to the body, with an interval of $45^o$ between each two adjacent legs. In such a manner the system is symmetrical and can be viewed as head-less and tail-less. The legs structure is the same for all the 8 legs, allowing the same capabilities in all the directions of motion. In order to assure a correct mobility, when the leg is in flight, every leg is defined with 4 DOFs with three links and three joints (i.e. one universal and two revolute pairs). In Fig. 3 the chosen leg model is shown.
When the leg is in contact with the surface an additional spherical joint has to be considered in order to properly model the contact condition. When the leg system touches the substrate and adheres to it, a closed kinematic chain is created and the contact point is known and fixed.
The study of the kinematics of the spider model is the basis for an effective control of the position of the body and the approach angle allowing the direct computation of the approaching angle, of the body center of mass and the validation of the chosen structure. For each leg the coordinate systems can be fixed according to the Denavit-Hartenberg (DH) convention (Fig. 4, [16]). The DH parameters, starting from the body reference system, are represented in Table II. Depending on the operative condition, the system can be

TABLE II
DH PARAMETERS FOR A SPIDER LEG.

| | $d_i$ | $\theta_i$ | $a_i$ | $\alpha_i$ |
|---|---|---|---|---|
| Body $\rightarrow$ 0 | 0 | $\theta_0$ | $len_{hip}$ | 0 |
| 0 $\rightarrow$ 1 | 0 | $\theta_1$ | 0 | $\frac{\pi}{2}$ |
| 1 $\rightarrow$ 2 | 0 | $\theta_2$ | $len_f$ | 0 |
| 2 $\rightarrow$ 3 | 0 | $\theta_3$ | $len_t$ | 0 |
| 3 $\rightarrow$ 4 | 0 | $\theta_4$ | $len_m$ | 0 |

viewed with different approaches. Two possible targets can be defined:

1) Free-flight kinematics: the body is considered known and fixed, and the target is to solve the direct and inverse kinematic problem for the free flight condition of a leg, hence for a open-chain configuration;
2) Contact-kinematics: the position of the contact points between the supporting legs (legs in contact with the substrate) and the substrate is considered fixed and the

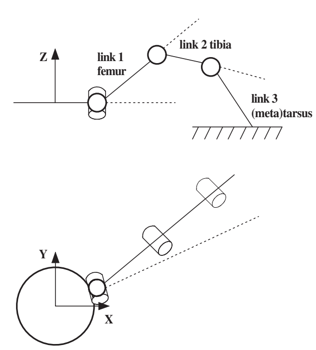


Fig. 3. Reduced model of the spider leg.

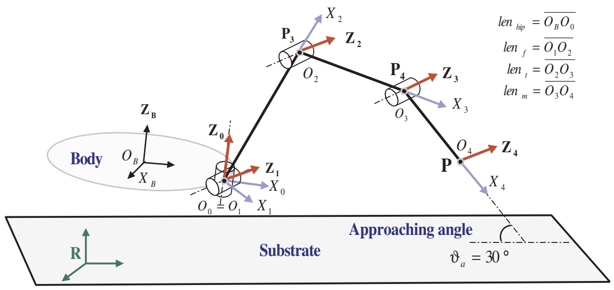


Fig. 4. DH coordinate systems of a spider leg.

target is to control the position and orientation of the body by solving the direct and inverse kinematics of the system.

### A. Free flight kinematics

In this analysis the body position and orientation are known and the purpose is to control the (meta)tarsus of each leg.

*1) Direct kinematics:* Once defined the values of the revolute pairs, the position of the end-effector can be easily computed. Defining $A_i^j$ as the roto-translation matrix between the joint $j$ and $i$, the direct kinematics equation becomes (Fig. 4):

$$\mathbf{A}_4^R = \mathbf{A}_B^R \cdot \mathbf{A}_0^B \cdot \mathbf{A}_1^0 \cdot \mathbf{A}_2^1 \cdot \mathbf{A}_3^2 \cdot \mathbf{A}_4^3$$

The matrix $A_B^R$ is known and the body can be considered as the Base coordinate system. The direct kinematics problem becomes:

$$\mathbf{A}_4^B = \mathbf{A}_0^B \cdot \mathbf{A}_1^0 \cdot \mathbf{A}_2^1 \cdot \mathbf{A}_3^2 \cdot \mathbf{A}_4^3$$

with the $\theta_0$ parameter of the $A_0^B$ fixed and related to the considered leg. Being fixed the relation between the B and 0 coordinate systems, the rototranslation matrix between the coordinate system 4 and 0 is:

$$\mathbf{T}_4^0 = \mathbf{A}_1^0 \cdot \mathbf{A}_2^1 \cdot \mathbf{A}_3^2 \cdot \mathbf{A}_4^3 = \left[\begin{array}{ccc|c} \mathbf{a}^0 & \mathbf{n}^0 & \mathbf{s}^0 & \mathbf{P}^0 \\ 0 & 0 & 0 & \end{array}\right]$$

where the approaching vector $\mathbf{a}^0$ is related to the $X$ axes of the last coordinate system and

$$\mathbf{P}^0 = \left[p_x^0, p_y^0, p_z^0, 1\right]^T$$

*2) Inverse kinematics:* Considering the body as fixed the task is to find the values of the joint angles in order to bring the tip of the (meta)tarsus to a defined position and orientation.
The inverse kinematics problem solution can be found by looking at the particular configuration of the leg system (Fig. 4). In the $XY$ plane of the body reference system works only the first ($\theta_1$) revolute pair. Hence $\theta_1$ has 2 possible values:

$$\theta_1 = atan2(p_y^0, p_x^0), \pi + atan2(p_y^0, p_x^0)$$

The residual chain is made of a planar manipulator with three links (Fig. 3). The $2,3$ and 4 joints make a R-R-R dyad, hence the inverse kinematics can be analytically solved. Calling $\phi = \theta_1 + \theta_2 + \theta_3$ the overall rotation on the $\mathbf{Z}$ axis of the joint 2 coordinate system, the position of the center of the $4^{th}$ revolute pair (**P4**) becomes:

$$\mathbf{P4} = [p4_x, p4_y, p4_z, 1]^T = \mathbf{P}^0 - len_m \cdot \mathbf{a}^0$$

where $\mathbf{a}^0$ is known once defined the target and the approaching angle. For $\theta_3$ holds (c = cos; s = sin):

$$c_3 = \frac{p4_x^2 + p4_y^2 + p4_z^2 - len_f^2 - len_t^2}{2 \cdot len_f \cdot len_t}, s_3 = \pm\sqrt{1 - c_3^2}$$

Once $\theta_3$ has been computed, $\theta_2$ can be found.
With some manipulations two equations in two unknown quantities can be found:

$$c_2 = \frac{(len_f + len_t \cdot c_3) \cdot \sqrt{p4_x^2 + p4_y^2} + len_t \cdot s_3 \cdot p4_z}{p4_x^2 + p4_y^2 + p4_z^2}$$

$$s_2 = \frac{(len_f + len_t \cdot c_3) \cdot p4_z - len_t \cdot s_3 \cdot \sqrt{p4_x^2 + p4_y^2}}{p4_x^2 + p4_y^2 + p4_z^2}$$

directly linked to the $\theta_3$ solutions. Being:

$$\theta_4 = \phi - \theta_2 - \theta_3$$

for $\theta_4$ there are two solutions and all the unknowns are found.

### B. Contact kinematics

When a leg is in contact with the substrate, the kinematics of the system changes. In such a case an extra spherical joint between the (meta)tarsus and the surface has to be considered. Hence a different kinematic problem appears.
In Fig. 5 and in Table III the additional DH coordinate systems are imposed and the parameters defined.

TABLE III
ADDITIONAL DH PARAMETERS.

| | $d_i$ | $\theta_i$ | $a_i$ | $\alpha_i$ |
|---|---|---|---|---|
| $4 \rightarrow 5$ | 0 | $\theta_5$ | 0 | $-\frac{\pi}{2}$ |
| $5 \rightarrow 6$ | 0 | $\theta_6$ | 0 | $\frac{\pi}{2}$ |
| $6 \rightarrow 7$ | 0 | $\theta_7$ | 0 | 0 |

The position and orientation of the spider's body (6 DOFs) have to be controlled, whereas the contact point between the spherical joint and the substrate is known. From the

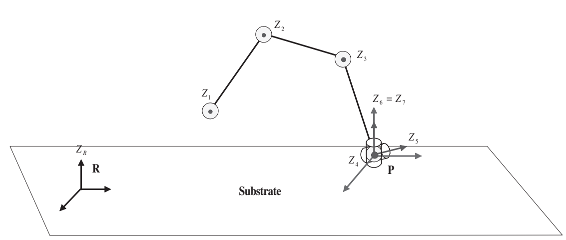


Fig. 5. Model of the leg in contact.

mobility analysis this system has 7 DOFs and, for the task to satisfy, admits $\infty^1$ solutions.

*1) Direct kinematics:* The direct kinematics can be expressed as:

$$\mathbf{T}_B^R = \mathbf{T}_6^R \cdot \mathbf{T}_5^6 \cdot \mathbf{T}_4^5 \cdot \mathbf{T}_3^4 \cdot \mathbf{T}_2^3 \cdot \mathbf{T}_1^2 \cdot \mathbf{T}_0^1 \cdot \mathbf{T}_B^0$$

and exploiting the considerations and results of the free-flight kinematics solution:

$$\mathbf{T}_B^R = \mathbf{T}_6^R \cdot \mathbf{T}_5^6 \cdot \mathbf{T}_4^5 \cdot (\mathbf{T}_4^B)^{-1}$$

By defining the values of the angles of the pairs, it is possible to compute the position and orientation of the spider's body.

*2) Inverse kinematics:* In order to compute the values that must be imposed to the joints in order to bring the body to a desired position and orientation, the chain has to be evaluated from the Body coordinate system.

For every leg the distance between the body reference system and the origin of the coordinate reference system related to the first revolute joint of every leg is fixed. By defining the target as:

$$\mathbf{Body} = [\mathbf{B};\Theta] = [B_x, B_y, B_z, \phi_B, \theta_B, \psi_B]^T$$

the roto-translation matrix between the Reference system and the body can be expressed as:

$$\mathbf{T}_B^R = \left[\begin{array}{ccc|c} c_\phi \cdot c_\theta \cdot c_\psi - s_\phi \cdot s_\psi & c_\phi \cdot c_\theta \cdot s_\psi - s_\phi \cdot c_\psi & c\phi \cdot s_\theta & B_x \\ s_\phi \cdot c_\theta \cdot c\psi + c\phi \cdot s\psi & s_\phi \cdot c_\theta \cdot s_\psi - c_\phi \cdot c_\psi & s_\psi \cdot s_\theta & B_y \\ -s_\theta \cdot c_\psi & s_\theta \cdot s_\psi & c_\theta & B_z \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$

Being known the rototranslation matrix between the body and the first joint, the matrix $\mathbf{T}_0^R = \mathbf{T}_B^R \cdot \mathbf{T}_0^B$ is available. The value of the $\theta_1$ angle is found considering Fig. 5. $\theta_1$ is the rotation that allows to move the reference system 1 on the reference system 0.

The point $\mathbf{P}$ can be expressed in the coordinate system 0 as:

$$\mathbf{P}^0 = (\mathbf{T}_0^R)^{-1} \cdot \mathbf{P} = \mathbf{T}_R^0 \cdot \mathbf{P}$$

and $\theta_1$ can be calculated as in the free flight condition:

$$\theta_1 = atan2(p_y^0, p_x^0), \pi + atan2(p_y^0, p_x^0)$$

The $\mathbf{O}_0$ = $\mathbf{O}_1$ points, the $\mathbf{Z}_0$ axis and the contact point between the end of the (meta)tarsus link and the surface (i.e. $\mathbf{P}$ = $\mathbf{O}_4$ = $\mathbf{O}_5$ = $\mathbf{O}_6$ = $\mathbf{O}_7$) belong to the same plane $\pi$. By exploiting that, the $\mathbf{Z}_4$ = $\mathbf{Z}_3$ = $\mathbf{Z}_2$ = $\mathbf{Z}_1$ axis can be found.

The $\mathbf{Z}_4$ axis is the third column of the rototranslation matrix $\mathbf{T}_1^R$. The spherical joint in $\mathbf{P}$ is a virtual spherical joint that allows to define the rotations that have to be made in order to put the coordinate system 7 on the coordinate system 4. The three unknown angles are the Euler angles (ZYZ) with respect to the coordinate system 4.

In order to move the $\mathbf{Z}_7$ axis to the known $\mathbf{Z}_4$ axis two rotations are required ($\theta_6$ and $\theta_7$).

The spherical joint rototranslation matrix is:

$$\mathbf{T}_7^4 = \mathbf{T}_5^4 \cdot \mathbf{T}_6^5 \cdot \mathbf{T}_7^6$$

The $\mathbf{Z}_4^7$ axis is:

$$\mathbf{Z}_4^7 = \mathbf{T}_R^7 \cdot \mathbf{Z}_4^R$$

The $\mathbf{T}_4^7$ is equal to the transposed matrix $(\mathbf{T}_7^4)'$ and then the $\mathbf{Z}_4^7$ can be also expressed as:

$$\mathbf{Z}_4^7 = \left[-s_{\theta_6} \cdot c_{\theta_7}, s_{\theta_6} \cdot s_{\theta_7}, c_{\theta_6}, 1\right]^T$$

By comparing the two expressions for $\mathbf{Z}_4^7$, the angles $\theta_6$ and $\theta_7$ can be found. The unknown system is now reduced to the four-sided made of the revolute joints defining the angles $\theta_2$, $\theta_3$, $\theta_4$ and $\theta_5$. All these joints are in the same plane and all the associated reference systems have the same $\mathbf{Z}$ axis. This articulated mechanism has one DOF and admits $\infty^1$ solutions. This DOF can be used for choosing the best configuration available in order to assure conditions on the overall adhesion of the leg and the system. Hence, being known the points $\mathbf{O}_1$ and $\mathbf{O}_5$, this DOF is used to impose the approaching angle $\theta_5$. The spherical wrist is defined and the $\mathbf{O}_3$ origin becomes available. The solution of the remaining problem is an inverse kinematics of a R-R-R dyad, the same already solved for the free flight configuration.

### C. Overall kinematics

Once available the free-flight and the contact kinematics the kinematics of the overall structure can be solved and implemented by construction. In order to deal with realistic conditions an analysis of the typical locomotion gait and natural postures have to be made.

## V. KINEMATIC SIMULATOR

A kinematic simulator has been developed in order to test the kinematic solution and the developed model (Fig. 6).

The locomotion is simulated by considering the contact with a flat inclined surface and available future adhesion systems replicating the abilities of the spider. The implemented stepping gait is the spiders' *alternate tetrapod* gait [4], consisting of two main phases with four flight legs and four legs in contact in order to form a tetrapod (e.g. in the first half of the step the legs first and third on the right -R1,R3- and the legs second and fourth on the left -L2,L4- are in contact; in the second half R2-R4-L1-L3 are in contact) with the surface according to an alternate pattern.

A *fundamental step* has been implemented and the cycle of actions made by the spider in this time sequence is made by two phases: the Support and the Motion phase (Detaching-Return-Attaching).

In the Support phase the legs are in the best adhesion condition (approaching angle between 25° and 35°) and support the body during the fundamental translation. The four legs in contact exploit the support phase in different manners.

The *L1* (fore left leg) or *R1* (fore right leg) moves from an extended to a retracted condition.

The *L4* (back left leg) or *R4* (back right leg) pushes the body far from the initial position, switching from a retracted condition to an extended one.

The *L3* (lateral back left leg) or *R3* (lateral back right leg)

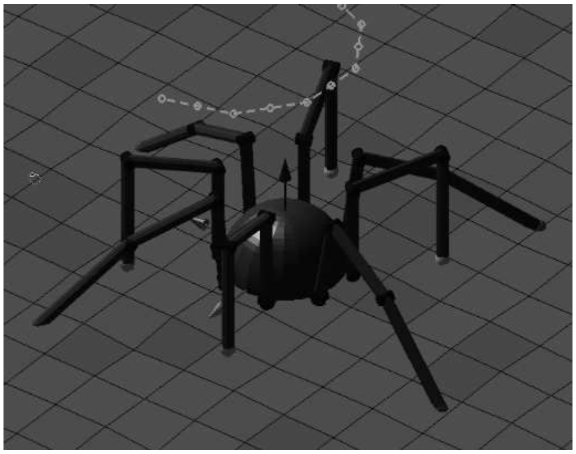

Fig. 6. Spider-robot simulator.

makes two movements. The leg pushes the body switching from a retracted to an extended condition and allows an advancing of the body also with a lateral rowing movement. The *L2* (lateral front left leg) or *R2* (lateral front right leg) pulls the body switching from an extended to a retracted condition and allows an advancing of the body also with a lateral rowing movement.

In the return phase the legs start from a contact condition but with an angle between the (meta)tarsus and the substrate bigger than $70°$.

Hence they can be lifted with little efforts. The four legs of the pattern are lifted up from the substrate, retracted near the body, rotated about the first revolute pair of the kinematic chain and finally extended in order to reach the correct position for the subsequent support phase. The next position of each leg is calculated and implemented taking into account the behavior that the leg has to follow and the direction of locomotion. Moreover the next positions are studied in order to allow the inverse kinematic solutions and avoid collisions between the legs. By overlapping part of the two half phases of a step a transition phase with eight legs in contact with the substrate is defined and a better adhesion condition can be simulated.

The results confirm as the chosen kinematic and locomotion model are feasible and efficient. The DOF available for each leg allows to choose the correct approaching angle and the wanted point of contact on the surface. Moreover, the radial configuration and the same kinematics of the legs can allow to move to the target point by selecting the shortest path thanks to the end-less condition implemented.

## VI. CONCLUSIONS AND FUTURE WORK

This work studied the spider system in a bio-mimetic perspective.

Looking at the climbing abilities of the spider, directives and constraints in order to replicate the dynamics of the attach were found. Taking into account such directives, the evaluation of the kinematics of the real spider has been done in order to define a new spider-model for a future robotic prototype. The overall kinematics of the developed spider-system has been solved starting from the analysis of the simplified leg model. A locomotion strategy inspired by the real pattern of the spider has been studied and evaluated for the simplified system taking into account the degree of adhesion of each leg.

The spider-model, the overall kinematics and the locomotion strategy have been implemented in a simulator that confirmed the validity of our choices.

Current and future work will cover the study of the static and dynamic control of the model, also taking into account emerging bioinspired control techniques, and the integration of artificial adhesive elements in a robotic structure, in order to understand and fix other directives on the practical realization of the system.

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