Abstract: Crawling mechanisms with energetic and control autonomy may move and steer by sliding on the ground. The paper presents an analytic and MBS simulation study on the possibilities and limits of steering a tetrahedral mechanism on a slope. The mechanism movement is analyzed using an equivalent 3d model. The analysis is structural, kinematical, static and dynamic. The limit conditions for stability on the slope, tilting, and maximal path curvature are defined. Some possible strategies of moving to a point are proposed.

Keywords: 3d mechanism, crawling, MBS simulation, steering

I. Introduction

Mankind has always manufactured means to displace material goods or persons, with various types of actuation (combustion engine, electric, hydraulic motor, etc.), with their reliability and safety increased by new materials, technologies and control devices.

The motion of mechanical devices may be improved by getting inspiration from biological structures. Studies of biomechanics investigated principles of motion, speed and energetic efficiency related to elements number and size, symmetry in displacement, ratio of segments' length and so on. Dickinson et al. offered an early general view on animals' movement [1]. Zielinska reviewed walking machines and made observations on displacement pattern of a large group of animals starting with simple invertebrates up to complex mammals [2]. Further extensive and substantial studies on imitation of human locomotion in robots' gait were presented by Zielinska et al [3], [4], and [5].

Modules based on biological inspiration are developed. The design of such structures is only at the beginning, but it spans quickly and intensively the significant potential of the new concept is understood. Different parts of human or animal body are sources of inspiration for intelligent mechanical structures moving through sliding, crawling, climbing and stepping with a large variety of gaits. Human body was the inspiration for the humanoid robots. Human walking imitation in a robotic module was presented by Ceccarelli et al. [6], [7]. Ottaviano et al. designed and tested a hybrid leg-wheel walking machine [8]. Ceccarelli reviewed the progress in legged walking, emphasizing the influence of the kinematic and dynamic characteristics of the mechanical structure on the performance of the locomotion artifact [9]. The human body inspiration extended to other segments than legs. So, Liang and Ceccarelli proposed a robotic parallel structure achieving motion tasks performed by the human torso [10].

Other movement types were studied to be imitated in robotic applications. Crawling or sliding-crawling are natural moving possibilities which became of interest. Studies on fundamental physics involved in crawling structures are available. An insight on locomotion physics taking into account mass, elastic connections, anisotropic friction, degrees of freedom, asymmetry of kinematics and friction forces was given by Wagner and Lauga [11]. Jlpeerts combined biology and robotics to develop a crawling device based on the model of a salamander, both from mechanical and control point of view [12].

Quillin's focused on crawling models taken from nature and provided studies on locomotion kinematics and various parameters describing its efficiency in terms of speed and energy consumption. Scaling natural structures is used as performances may vary significantly with respect to the size of structure elements [13].

There are already practical results in crawling robots field. There are numerous solutions, more or less similar to natural displacement, which use various types of mechanisms such as parallelogram, pantograph etc. The resulting gait may be sliding or sliding-crawling as described by Tian et al. [14]. Zimmermann et al. studied natural crawling movement of snakes or worms to use them as inspiration on the design of robots operating in unpredictable environments. Their solution uses a magnetizable elastic body traveling in magnetic field [15].

Liu et al proposed a robotic earthworm with a bio-mimetic sensing system, working on a principle based on peristaltic contractions and elongations of worm's compliant segmented body [16].

A crawling micro robot able to move along a tube, e.g. a human blood vessel, by means of asymmetric friction forces controlled by an oscillating external magnetic field was developed by Nam et al. [17]. Wang et al created a kinematic model, then a prototype of a mini-robot which crawls similarly to caterpillars [18].

Designing crawling robots went beyond imitation of mechanical structures. Neuronal connections of different segments can also be mimicked, as stated by Lipson and Pollack [19], and an algorithm for structures evolution by
selection was investigated.

Crawling robots are a current subject of interest in engineering. Locomotion principles are taken from certain species, according to the skill considered to be most significant. The mechanical structures proposed until now are based on simple planar mechanisms, involving linkages and wheels. Thus, there is a broad development perspective in designing efficient and compact solutions.

II. Proposed crawling tetrahedral mechanism

The authors published previous results on crawling mechanism [20], [21], [22] for studies on steering and non-steering mechanisms with compliant joints and linear actuation crawling on a horizontal plane surface.

The proposed basic mechanism is tetrahedron with a pushing element linked on its point. The movement obtained through sliding the structure on the ground depends both on the friction in the contact points and ground surface planarity.

The mechanism with one active element on an edge [22] (Fig. 1a) or on the pushing element (Fig. 1b) touches the ground in 4 points, 3 on the basic link and the 4-th on the push. For sliding when actuated, the friction force between the push and the ground has to be greater than the sum of all friction forces in contact points with the base. This mechanism cannot steer.

In Figure 2, two steering solutions are shown. Steering supposes the position and rotation vectors control, so the mobile’s characteristic point (CP) should move along the desired path as the characteristic axis (CA) remains tangent to the path. If the CP leaves the path or the CA twists, the steering should compensate counter sideways movement or counter twist by lateral or oblique pushing and/or by altering the reactions on the bases touch points.

As the two actuators on the front lateral edges (Fig. 2a) move at the same time, the structure glides as a non-steered one. When only one side acts, the passive pushing element presses obliquely on the ground relative to a CA rotated in the direction of the leading edge and the lateral component (in z axis direction) of the frictional force moves the structure sideways.

In the Fig. 2b, a servomotor turns a bended push so the touch point on the ground is no longer on CA. As the acting edge shrinks the reactions on the three contact points between the basis structure and the ground are uneven, thus the structure will twist.

Several non-steering and steering mechanism models built and tested both in TU Dresden and UP Timișoara by joint teams also include power batteries to achieve some moving independence and carry all the electronics and sensors needed to act and control their movement (Figure 3).
Multibody System (MBS) simulations were used for evaluating the crawling and steering capabilities of some mobile mechanisms moving on horizontal surfaces.

### III. Analytical study of tetrahedron crawling on a slope

For the study, a structure with rigid triangular base (see Figure 5 a) and b)) is proposed. The base triangular element 2 lays on the ground 1 by three contact points P₁, P₂ and P₃, 5 DoF each. In the back corner of the base triangle, the active edge AT₁ is coupled by the revolute joint A (1 DoF). The active cylindrical joint C (2 DoF), modeling a pneumatic muscle or cylinder, connects the elements 3 and 4. On the front side of the base triangle, a triangular side face 5 turns around the cylindrical joint B (2 DoF) which is connected to the active edge by the cylindrical joint T₁ (2 DoF).

The cylindrical joint T₂ with 2 DoF allows the rotation of the push 6 as it may lay on the ground on the contact point D (5 DoF). The push may be shifted along the joint axes, so D is not always on the base triangle's symmetry axis, but at a distance e.

![Figure 5. Kinematical scheme a) and CAD model b) of the proposed tetrahedral crawling mechanism](image)

The mechanism has the degree of freedom:

$$F = 6 \cdot (n-1) - \sum_{i=1}^{5} (6-f_i) = 6 \cdot 5 - (5+1+4+4+1) = 5.$$  \hspace{2cm} (1)

The structure has a constraint motion because:

$$n_a < F \leq n_a + n_{in} = 5.$$  \hspace{2cm} (2)

where \(n_a\) is the number of acting movements and \(n_{in}\) is the number independent movements: slide, drift and twist, determined by kinetostatical conditions.

The movement conditions for the mechanism with solid base, one active edge and shifting push are similar to those studied in [22] in order to generate sliding movement and steer it on the desired path. The mechanism's movement depends on the two acting elements, i.e. the length \(l_{3,4}\) of the active edge and the shift \(e\) of the push and also on the position of its center of mass.

![Fig. 6. The tetrahedral crawling mechanism on a slope with the push shifted downhill](image)

The considered coordinate system (s. Figure 5) has the origin in the base’s symmetry center as the mobile’s characteristic point (CP) and the plane xOz on the ground. The symmetry axis of the base’s equilateral triangle will be the x-axis and is considered to be the characteristic axis (CA).

The mechanism is placed on a slope with the angle \(\beta\), and, at the considered moment, the CA makes the angle \(\alpha\) with the slope line. If \(\alpha\) is between \(\pm 90^\circ\), the mechanism faces uphill. For \(\alpha=90^\circ\), the CA is normal to the slope and horizontal. At higher angles, the mechanism faces downhill. Obviously, the slope angle \(\beta\) must be lower as the friction angle \(\varphi_N\):

$$\beta < \varphi_N = a \tan \mu_N,$$  \hspace{2cm} (3)

where \(\mu_N\) is the friction coefficient on the contact points P₁, P₂ and P₃, so the mechanism should not slide downhill under its own weight.
The pushing direction is parallel to the CA. The mechanism’s movement on the ground depends on the friction forces in the 4 contact points, so the movement will be conditioned by its weight $G$ value and position $P_G$, given by its coordinates $x_{G0}$, $y_{G0}$ and $z_{G0}$ on the base coordinates system.

On the slope, the weight remains vertical as the base 2 tilts. The projection of $P'_G$ now shifts with:

$$\Delta G = y_{G0} \cdot \sin \beta,$$

and its new coordinates on the base plane are:

$$\begin{align*}
    x_G &= \Delta G \cdot \cos \alpha = y_{G0} \cdot \cos \alpha \cdot \sin \beta, \\
z_G &= \Delta G \cdot \sin \alpha = y_{G0} \cdot \sin \alpha \cdot \sin \beta,
\end{align*}$$

(4) (5)

The projection would be off the CA, unless $\alpha$ or $\beta$ are null.

On the mechanism act the resultant joint reactions $R_j$ in the three contact points between the basis contour and the ground and $R$ – in the tip of the pushing element, with the components $N_j$, respectively $N$ normal to the contact surface and $F_fj$, respectively $F_f$ – the friction forces in these points (see [22] and Figure 7) and the tangential and normal components of the weight $G$.

$$\begin{align*}
    G_N &= G \cdot \cos \beta, \\
    G_T &= G \cdot \sin \beta,
\end{align*}$$

(6)

The tangential $G_T$ weight component passes through $P_G$ and points down the slope at the angle $\alpha$ to the CA.

The conditions to keep the mechanism on the ground are $N_j > 0$.

Generally, the structure’s weight vector direction must pass through the interior of a certain contour (smaller than the basis contour), depending on the pushing angle.

The structure’s sliding movement has two components: the velocity $v_O$ of the CP on the trajectory, which depends on the actuator’s velocity $v_a$, and the angular (twisting) velocity $\omega_k$:

In the $xOy$ plane, the following points are defined:

- the contact points $P(x_j,y_j)$ between the structure’s solid base and the ground;
- the contact point $P(x_{pG},y_{pG})$ between the pushing element and the ground;
- the projection of the tetrahedron’s center of gravity $P'_G(x_{G0},y_{G0},z_{G0})$ on the ground;
- the instantaneous rotation center $M(x_M,y_M,z_M)$ of the structure.

The joint reactions are determined by the solving the following 6 equation system:

$$\sum M_{j} = 0 \Rightarrow N_j \cdot H_b + N \cdot \Delta_{\eta j} - G_N \cdot \Delta_{Gj} = 0, j = 1,3,$$

(8)

$$\sum F_d = 0 \Rightarrow \mu_p \cdot N - G_T \cdot \cos \alpha = \mu_b \cdot \sum N_j \cdot \cos \theta_j,$$

(9)

$$\sum F_{1d} = 0 \Rightarrow \mu_b \cdot \sum N_j \cdot \sin \theta_j = G_T \cdot \sin \alpha,$$

(10)

$$\sum M_{gM} = 0 \Rightarrow \mu_b \cdot \sum N_j \cdot \rho_j = \mu_p \cdot N \cdot \Delta_{Md} - G_T \cdot \Delta_{Mg},$$

(11)

with: $\mu_{b,p} = \tan \phi_{b,p}$, the friction coefficients for the pairs base/ground and pushing element/ground, $H_b$ – the basis height, $\Delta_{\eta j}$ and $\Delta_{Gj}$ the distances from the points $P$ and $P_G$, respectively, to the lines $d_j$ on the structure’s basic contour, passing through the contact points opposed to $P_j$, given by the equations:

$$\begin{align*}
    (d_j) &= x \cdot (y_{b_{j1}} - y_{b_{j2}}) - y \cdot (x_{b_{j1}} - x_{b_{j2}}) + \\
    &+ (x_{b_{j1}} - y_{b_{j1}} - x_{b_{j2}} - y_{b_{j2}}) = 0,
\end{align*}$$

(12)

and $\phi_j$ – friction forces direction relative to the CA.

$$\theta_j = \left\{ \begin{array}{ll}
    - \frac{x_{M} - x_{b_j}}{y_{M} - y_{b_j}}, & j = 1,3 \\
\end{array}\right.$$

(24)

$\rho_j$ are the contact points radii measured from the instantaneous rotation center $M$:

$$\rho_j = \sqrt{(x_{M} - x_{b_j})^2 + (y_{M} - y_{b_j})^2}, j = 1,3$$

(25)

The 6 unknown parameters in this system are the normal components $N$ and $N_j$ and the coordinates $x_M$ and $y_M$ of the instantaneous rotation center, and may obtained by
numerically solving the system.

The proposed analytical approach is however of little practical use, as it relies on the friction coefficients' values, highly variable mainly for a movement with frequent stops. The friction and the damping in the joints is also neglected, as well as the slight variations of the center of gravity position due to the internal movements in the mechanism.

Moreover, the contact point P of the push and the ground changes position during movement, so the calculations would take a lot of time.

In the following, in order to predict the behavior of the crawling mechanism, the Rigid Body System (RBS) simulation method is used.

IV. RBS simulations for tetrahedral mechanisms crawling on slopes

For the study, a CAD model in SolidWorks is used. The tetrahedron's edge is 200 mm, and the push is 178 mm long. The actuator on the back edge has a oscillating movement with 1Hz frequency and 10 mm stroke. The push may shift laterally 40 mm on each direction.

The lightweight parts are made of PE and PVC plastics. The static and dynamic friction coefficients values for the contact between ground and tetrahedron base, respectively the push are given in Table 1

<table>
<thead>
<tr>
<th>Friction pair</th>
<th>Base/ground static</th>
<th>Push/ground static</th>
<th>Base/ground dynamic</th>
<th>Push/ground dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction coefficient</td>
<td>0.15</td>
<td>0.1</td>
<td>0.6</td>
<td>0.4</td>
</tr>
</tbody>
</table>

TABLE I. Friction coefficients

The mechanisms crawls on a $4:100 = 0.04 = 4\%$, less then the minimal friction coefficient.

Some cases with central, uphill or downhill positioned pushing element at different eccentricities were studied

A. Tetrahedral crawling mechanism with central push

The eccentricity $e=0$. The mechanism starts with the CA perpendicular to the slope.

Even if the slope is not very steep, the mechanism with central push crawls downhill.

B. Tetrahedral crawling mechanism with uphill push

The eccentricity is $e=12.5$ mm on the uphill side of the mechanism. The mechanism starts with the CA perpendicular to the slope. Even by smaller eccentricities, the path curvature is more pronounced as the mechanism with uphill push crawls rushing downhill.
C. Tetrahedral crawling mechanism with downhill push
The eccentricity \( e = 12.5 \text{ mm} \) on the uphill side of the mechanism. The mechanism starts with the CA perpendicular to the slope.

D. Tetrahedral crawling mechanism with downhill push at the right distance
The eccentricity \( e = 20 \text{ mm} \) on the downhill side of the mechanism. The mechanism starts with the CA perpendicular to the slope.

By smaller eccentricities, the path curvature is smaller as the mechanism crawls downhill.
By the right eccentricities, the path may be almost straight as the mechanism with downhill push crawls across the slope.
III. Conclusions
The movement capability of the tetrahedral crawling mechanisms is given by its geometry, the horizontality and the planarity of the ground and by the friction conditions. The dependence of the steering on the position of the gravity center, on the slope and on the friction conditions in the 4 contact points with the ground shows, as experiments confirmed, that controlling the movement only by programmed actuators is not precise. In order to increase the steering accuracy, feedback information about the CP’s position and the CA’s direction must be collected from the programmed actuators is not precise. In order to increase the steering accuracy, feedback information about the CP’s position and the CA’s direction must be collected from the

II. Dynamic Studies

The 4 contact points with the ground shows, as experiments confirmed, that controlling the movement only by programmed actuators is not precise. In order to increase the steering accuracy, feedback information about the CP’s position and the CA’s direction must be collected from the environment and the actuators movement adjusted so the structure stays on track.

Modeling and simulations allow a more accurate estimation of the steering capabilities and the obtainable speed of the mechanism in the design stage. Crawling uphill allows higher path curvatures as crawling downhill. Turning the mechanism is thus easier and the control is more precise.

If only the end position and direction is desired, it is advisable first to climb or descent at the target altitude and then to crawl across the slope. Simulations with high speed and low stroke actuators have shown that the movement may be more stable, as the inertia does not allow the sliding to stop in the retracting phase of the actuator. At even higher speed, the push is no longer needed, as the mechanism acts like a vibrating plate on the ground. Dynamic studies for these cases will be published by the authors in further works.

References


