Simona-Mariana Crețu

APPLICATIONS of TRIZ to MECHANISMS & BIONICS

Academica Greifswald
2007
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<th>National Library- CIP Description</th>
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<td><strong>Applications of TRIZ to Mechanisms &amp; Bionics/Crețu S-M</strong></td>
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<tr>
<td>Greifswald, Academica, 2007</td>
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<td>p.173:14x20 cm</td>
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<td>Bibliogr.</td>
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<tr>
<td>I.S.B.N. 978-3-940237-03-3</td>
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<td>CZ. 62-231.3</td>
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</table>

The work presented in this book has been reviewed by International Scientific Committees

First published 2007

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FOREWORD

Many researchers successfully solve many of the problems of science and technique with the help of creativity techniques. Sometimes these techniques are applied by innovators intuitively, but it is much better to coordinate the process of creativity using different tools, reducing so the time of creation substantially.

The book is structured in four parts:
1. Introduction to the TRIZ method
2. TRIZ Applied to Establishing the Mobility of some Mechanisms
3. TRIZ Applied to Function Generating Mechanisms
4. Creativity in Bionics.

The creativity techniques, especially TRIZ method (the Theory of Inventive Problem Solving), can be applied to resolving difficult problems – in mechanisms, robotics and bionics.

In this book there are many examples and programs specifically chosen for mechanisms, robotics, bionics and for the field of academic education.

Lately, scientists’ interest in the mobility calculation of different mechanisms hasn’t ceased. We consider that the TRIZ method can be utilized even in the case of the calculation where it is required elimination of some contradictions, such as the calculation of the mobility of the mechanisms.

The mechanisms with variable links length are frequently used in technical applications for function generation. Many systematic studies about them have been done in the last 3 decades.

The TRIZ method was utilized to eliminate some physical constraints: the interference of the profiles, the interference between cable and profile caused by changing the sign of the radius of curvature.
The steps of the strategy in the process of scientific creation used in bionics, some applications to robotics and academic education are exposed. Experimental analysis, thought experiments, visual analogy, inventive principles recommended by TRIZ, maintenance of the idea in long-term-memory and intensive attention on it, cognitive historical analysis, were utilized in the process of creativity.

Several structural legged robots were developed, more or less intricate, with movement in plane or in space, inspired from the movement of thousand-legged worms and caterpillars.

The Author hopes that the book will acquaint the readers (researcher, scientists, engineers, teachers, graduate students) with some applications of the TRIZ method in the field of mechanisms, robotics, bionics and in academic education.

S.-M. C.
1 INTRODUCTION TO THE TRIZ METHOD

Each scientist undoubtedly looks for innovative ideas in order to create something new, useful in his/her domain of study.

We know that there are more than 200 creativity techniques used by scientists for obtaining scientific novelties. Sometimes these techniques are intuitively applied by innovators, but it is much better to coordinate the process of creativity using tools like: TRIZ, Analogies and many others.

A problem with no known solution is called inventive problem. The scientist Papp, from Egypt, over four hundred years ago, said it could be a science named heuristics, to solve inventive problems [1]. Consciously or intuitively, everyone eliminates contradictions when they obtain new solutions in the domain of science or technique.

Genrich Saulovich Altshuller (15.10.26-24.09.98) analyzed over 200000 patents to understand how the inventive problems were solved by eliminating the contradictions. He defined inventive problem as the one in which the old solution causes another problem to appear.

Altshuller discovered that many patents proposed a solution that eliminated the contradictions. In this way, a theory of inventive problem solving, which he named TRIZ (the Russian acronym for the Theory of Inventive Problem Solving) was developed.

The problems had been solved by using one or more of the forty fundamental inventive principles [1].

Altshuller identified, from over 1.500.000 diverse patents, 39 standard technical characteristics that cause conflicts, called the 39 Engineering Parameters.
TRIZ is a comprehensive, systematically organized invention knowledge and creative thinking methodology. With the TRIZ theory we follow:

- to obtain an ideal solution
- to find the contradictions
- to realize an organized systematic process of the innovation and to eliminate the contradictions.

The theory of driving towards the ideal solution is known as Ideality.

Ideality can be defined as:

$$\text{Ideality} = \frac{\text{Sum of Useful Effects}}{\text{Sum of Harmful Effects} + \text{Cost}}$$

The Contradiction Theory is a tool developed by Genrich Altshuller.

The user can generate multiple solutions to any contradiction.
There are three types of contradictions: physical, technical and administrative.

An administrative contradiction appears between the physical requirements of a problem and requirements as: costs, risks, time …

A physical contradiction exists when two conflicting states are looked for simultaneously in the same part of a system. To solve a physical contradiction some separation principles are used: separation in time, in space, between parts and whole, under certain conditions.

A technical contradiction occurs when science or engineering is used to improve one aspect of a system while worsening the desirability of another aspect.

When a contradiction is eliminated then will be no loss in performance or properties for the improvement of other properties.

First, a contradiction is identified as technical terms which then can be translated into generic terms and so the parameters can be selected.

Any technical contradiction that occurs is between two of the 39 parameters identified by Altshuller.

One technical characteristic improves and other worsens to solve it.

To find which inventive principle to use, the Contradiction Matrix was created [2].

It lists the 39 Engineering Parameters [1] on the X-axis (undesired effect) and on the Y-axis (features to improve).

In the intersecting cells the appropriate Inventive Principles are listed for using. Each principle must be interpreted and some of them must be translated into reality.

The utilization of these principles requires creativity and experience.

We present below the 39 Engineering Parameters (standard technical characteristics), the 40 Inventive Principles (by
The 39 Engineering Parameters (standard technical characteristics):

1. Weight of moving object
2. Weight of stationary object
3. Length of moving object
4. Length of stationary object
5. Area of moving object
6. Area of stationary object
7. Volume of moving object
8. Volume of stationary object
9. Speed
10. Force (Intensity)
11. Stress or pressure
12. Shape
13. Stability of the object’s composition
14. Strength
15. Duration of action of moving object
16. Duration of action by stationary object
17. Temperature
18. Use of energy by moving object
19. Use of energy by stationary object
20. Illumination intensity
21. Loss of Energy
22. Loss of substance
23. Loss of information
24. Loss of time
25. Quantity of substance /the matter
26. Reliability
27. Power
28. Measurement accuracy
29. Manufacturing precision
30. Object-affected harmful factors
31. Object–generated harmful factors
32. Ease of manufacture
33. Ease of operation
34. Ease of repair
35. Adaptability or versatily
36. Device complexity
37. Difficulty of detecting and measuring
38. Extent of automation
39. Productivity.

The 40 Inventive Principles (by Genrich Altshuller):

1. Segmentation
2. Taking out
3. Local quality
4. Asymmetry
5. Merging
6. Universality
7. ‘Nested doll’
8. Anti-weight
9. Preliminary anti-action
10. Preliminary action
11. Beforehand cushioning
12. Equipotentiality
13. ‘The other way round’
14. Spheroidality
15. Dynamics
16. Partial or excessive actions
17. Another dimension
18. Mechanical vibration
19. Periodic action
20. Continuity of useful action
21. Skipping
22. ‘Blessing in disguise’ or ‘Turn Lemons into Lemonade’
23. Feedback
24. ‘Intermediary’
25. Self-service
26. Copying
27. Cheap short-living objects
28. Mechanics substitution
29. Pneumatics and hydraulics
30. Flexible shells and thin films
31. Porous materials
32. Color changes
33. Homogeneity
34. Discarding and recovering
35. Parameter changes
36. Phase transitions
37. Thermal expansion
38. Strong oxidants
39. Inert atmosphere
40. Composite material
An example of the utilization of The Contradiction Matrix:

**Technical contradiction 29/36.**

**Improving Feature 29:**
**Precision of the generated function.**

**Worsening Feature 36:**
**Device complexity.**

---

**CONTRADICTION MATRIX**

(by Genrich Altshuller)

<table>
<thead>
<tr>
<th>Worsening Feature</th>
<th>1 (Weight of moving object)</th>
<th>2 (Weight of stationary object)</th>
<th>3 (Length of moving object)</th>
<th>4 (Length of stationary object)</th>
<th>5 (Area of moving object)</th>
<th>...</th>
<th>39 (Productivity)</th>
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<tbody>
<tr>
<td>1 (Weight of moving object)</td>
<td>+</td>
<td>-</td>
<td>15, 8, 29, 34</td>
<td>-</td>
<td>29, 17, 38, 34</td>
<td>...</td>
<td>15, 1, 28</td>
</tr>
<tr>
<td>2 (Weight of stationary object)</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>10, 1, 29, 35</td>
<td>-</td>
<td>...</td>
<td>1, 32, 10</td>
</tr>
<tr>
<td>3 (Length of stationary object)</td>
<td>8, 15, 29, 34</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>15, 17, 4</td>
<td>...</td>
<td>35, 28, 6, 37</td>
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<td>...</td>
</tr>
<tr>
<td>39 (Productivity)</td>
<td>35, 26, 24, 37</td>
<td>28, 27, 15, 3</td>
<td>18, 4, 28, 38</td>
<td>30, 7, 14, 26</td>
<td>10, 26, 34, 31</td>
<td>...</td>
<td>+</td>
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- **26 COPYING**
- **2 TAKING OUT**
- **18 MECHANICAL VIBRATION**
Trends of Engineering System Evolution are a component of The Theory of Inventive Problem Solving very useful for the engineers and inventors to improve or to abandon one existing technology.

There are two major trends:

- The trend of S-shaped evolution of engineering systems
- The trend of increasing ideality.

An engineering system passes through four stages:

- slow development
- rapid growth
- stabilization
- decline

which can be represented by an S-shaped curve.

By analyzing the actual technology level and by identifying the contradictions in the products, the TRIZ method can be used successfully for progress of science and technique.

Recently, TRIZ applications have extended into non-technical areas: business, service operation management, quality management, education.

Case studies are a very important element of any TRIZ implementation strategy. Without case studies, the TRIZ theory does not develop.

This approach provides mechanical examples, biomechanical examples and examples for the calculus in the technical field of the 40 inventive principles, combined with other creativity techniques like: visual analogy, experimental analysis, thought experiments …
2 TRIZ APPLIED TO ESTABLISHING THE MOBILITY OF SOME MECHANISMS

2.1 INTRODUCTION

This chapter deals with determining the global mobility of mechanisms using the TRIZ method. The contradictions which appear in the global mobility calculation, using inventive principles recommended by the TRIZ method, were eliminated. We present the formulae for a quick calculation of the global mobility and the signification of the notion mobility number for some mechanisms. We testify to the correctness of the new procedure by giving some examples.

Cebychev-Grubler-Kutzbach’s mobility criterion is a criterion for global mobility [3] calculation, containing some structural parameters of the mechanism (Eqs. (2.1)- (2.3)).

\[
M = 6(m - 1) - \sum_{i=1}^{p} c_i \quad (2.1)
\]

\[
M = b(m - p - 1) + \sum_{i=1}^{p} f_i \quad (2.2)
\]

\[
M = \sum_{i=1}^{p} f_i - \sum_{j=1}^{q} b_j \quad (2.3)
\]

where:

- \( m \) is the number of mechanism links,
- \( p \) is the number of mechanism joints,
- \( f_i \) is the connectivity [3] of the joint \( i \),
- \( c_i \) is the degree of constraint of the joint \( i \),
- \( b \) is the number of degrees of freedom of the space in which the mechanism functions,
- \( b_j \) is the mobility number for the loop \( j \),
\( q \) is the number of independent chains.

Because the mobility must be greater or equal to 1, if Eq. (2.2) had been correct for any spatial mechanism with a single loop we would have obtained the condition that the number of the links be more than six (for planar mechanism more than three).

In the earlier works the systematic determination of the mobility of a mechanism involved the classification of mechanisms in three classes: trivial mechanisms, exceptional mechanisms and paradoxical mechanisms [4], according to the satisfaction or not of the mobility Eq. (2.2).

The mechanisms that have a full cycle mobility and do not satisfy the mobility criterion are called overconstrained mechanisms.

De Roberval proposed the first overconstrained mechanism in 1670, Sarrus the second in 1853 and Bennett the most famous overconstrained mechanism in 1903.


In 1927 Bricard showed that the mobility equation is not correct for all the situations [5].

In [6] it is explained why the formulae for a quick calculation of the mobility do not work for certain mechanisms.

Waldron summarised all four-link overconstrained linkages that are made up of lower kinematic pairs.

Myard realized some paradoxical non-common mechanisms with five and with six rotational joints with mobility one [7].

Baker, Pamidi, Soni, Dukkipat, Lee, Yan, Savage, Hunt, Mavroidis, Roth and others analysed the overconstrained mechanisms and the mobility of mechanisms [5, 8, 9, 10, 11, 12, 13, 14, 15].

Mavroidis and Roth distinguish four classes of
overconstrained mechanisms [16]:
   - symmetric mechanisms (symmetrical topological chart is considered a necessary condition for overconstrained loops)
   - Bennett based mechanisms combined special geometry mechanisms
   - mechanisms derived from 6 joint manipulators which have less than 6 degrees of freedom for their end-effector motion.

The universal Somov-Malushev’s mobility equation (Eq. (2.4)) is valid for the overconstrained mechanisms because it contains the $s$ parameter - the number of overclosing constraints (some examples can be found in [17]).

$$M = B(m - 1) - \sum_{i=1}^{p} c_i - f_p + s$$

(2.4)

$B$ is a motion parameter of the space of a mechanism ($B=3$, for planar mechanisms, and $B=6$ for spatial mechanisms), and $f_p$ is the number of passive degrees of freedom.

Lately, scientists’ interest in the mobility calculation of different mechanisms hasn’t ceased ([6], [18], [19], [20]).
2.2 THE INVENTIVE PRINCIPLES UTILIZED IN DIFFERENT CALCULATIONS

In the *Mechanism and Machine Theory* there are different inventive principles which are applied to different calculations. Thus, in the structural and kinematical analysis *segmentation* and *assembly* of the elements are sometimes used.

Wittenburg (1977) and Haug (1989) used cut-joint methods. A mechanism is modelled by its graph. An element is defined as a node and a kinematic joint is defined as an edge. An edge is cut in each independent closed loop to form a tree structure, called spanning tree (Bae and Haug 1987, Tsai 1989). The joints that are cut are replaced by a set of constraint equations [21].

We mention the method of studying overconstrained mechanisms, using the solution of inverse kinematics problem (Raghavan, Roth and Mavroidis) [16, 22]. A 6 link linkage is kinematically equivalent to a 6 link 6 joint open serial manipulator whose end effector coordinate system is identical to its base coordinate system.

The splitting of one element was utilised by Dudita and Diaconescu (1987) for the calculation of the global mobility of mechanisms with a single loop [23].

The method based on single opened chain limbs (SOC, a set of serial binary links) in the structural analysis of parallel robotic mechanisms was utilized by Yang, Jin et. al. (2002) [24].

The splitting of the platforms (the reference platform or the mobile platform) was used by Gogu (2005) for the calculation of the global mobility of multi-loop parallel robots [6,18].
2.3 FORMULATION AND ELIMINATION OF THE CONTRADICTIONS IN THE GLOBAL MOBILITY CALCULATION OF MECHANISMS

The methods known for the calculation of the mobility of mechanisms are grouped in two categories: one based on setting up the kinematic constraint equations and their rank calculation and the other without need to develop the constraint equations, for a quick calculation of the global mobility.

The TRIZ method will be utilised in order to eliminate the contradictions which appear in the global mobility calculation of mechanisms.

The contradictions which must be eliminated in this case are:

- we want to improve the precision of calculation of the degree of mobility for any mechanism (reliability - 27), but on the other hand,
- we want to use:
  - the simplest possible relations (that means avoid to write the kinematic constraint equations, which are complicated), and
  - parameters easy to determine, that means worsening of characteristics device complexity (36) and ease of operation (33) respectively.

These two contradictions (27/33 and 27/36) can be eliminated by one or more inventive principles recommended by the Contradiction Matrix:

- 27 (cheap short-living objects), 17 (another dimension), 40 (composite materials) and
- 13 (the other way round), 35 (parameter changes), 1 (segmentation), respectively.

The following inventive principles were used for a quick calculation of the mobility of mechanisms:

- 1 (segmentation) – we can segment the mobile or reference
elements with the rank > or = 2, so that the number of the
elements, including those appeared by segmentation, become
equal to the number of the simple kinematic joints,

- 27 (cheap short-living objects) + 17 (another dimension) –
we operate only mentally, by simple action upon the
mechanism: for a short time we suppose that all the elements
are disjoined and free in space, including the segmented
elements; one single frame remains fixed; after this, we
recompose the mechanism.

We can conclude:

• We segment the elements with the rank > or = 2,
including the frame, until the number of the elements is equal
to the number of the joints.
• We disjoin all the kinematic elements of the mechanism,
including those which are segmented, even if they are
segmented frames, except the one attached to environment.
• There are allowed all the movements in space.
• The number of degrees of freedom of the new system is
6m, where m denotes the number of all movable elements,
including the temporarily segmented elements.
• We make an element rejoin the frame, and thus the
degrees of freedom of the temporary system are diminished by
the constraints of this joint; the procedure is repeated for all the
elements which can temporarily move in space (or in plane)
until we obtain a spanning tree structure.
The mechanism is thus partially rejoined.
• It is investigated to the spatiality of the extreme
segmented frame from the first open chain, which must be
rejoined (the independent relative motion between the extreme
element and the reference element of the open chain).

A part of the degrees of freedom of the segmented frame is
possible to be annulled by the previously assembled linkage (if
the mechanism is overconstrained).
• It is investigated carefully to the spatiality of the extreme
element (which was segmented) of one open chain attached to the previous loops.

The input movements in this open chain are determined by the movements of the previously assembled loops. In some cases, the input movements in one open chain represent the spatiality of the element to which it is coupled, the element which is integrated only in the previous assembled loops. This step is repeated for all open chains which must be rejoined.

- The spatiality of all extreme elements of the open chains is eliminated from the previously calculated degrees of freedom, and thus the mechanism is rejoined.
2.4 THE FORMULAE FOR A QUICK CALCULATION OF THE MOBILITY OF SOME MECHANISMS USING THE TRIZ METHOD

According to the TRIZ methodology for the global mobility calculation of mechanisms (presented above) we can write:

\[ M = 6m - \sum_{i=1}^{p} c_i - \sum_{j=1}^{q} b_j - \sum_{k=1}^{p} f_{kp} \]  \hspace{1cm} (2.5)

where:
- \( q \) is the number of independent chains,
- \( p \) is the number of joints of the mechanism,
- \( m \) is the number of all movable elements, including the segmented elements; it is equal to the number of joints of the mechanism, \( p \),
- \( c_i \) is the degree of constraint of the joint \( i \),
- \( f_{kp} \) is the number of passive degrees of freedom in the joint \( k \) which do not change the movement of the next element which must be assembled in the open chain,
- \( b_j \) is the spatiality of the additional extreme element of the first considered open chain associated to the closed loop,
- \( b_j \) is the spatiality of the additional extreme element of the open chain \( j \) (associated to the closed loop \( j \)), attached to the previously assembled loops \( (j-1); j=2, ..., q \).

Because \( c_i = 6 - f_i \) and \( m = p \), Eq. (2.5) is reduced to Eq. (2.6). \( f_i \) is the connectivity of the joint \( i \).

\[ M = 6m - \sum_{i=1}^{p} (6 - f_i) - \sum_{j=1}^{q} b_j - \sum_{k=1}^{p} f_{kp} \]

\[ M = \sum_{i=1}^{p} f_i - \sum_{j=1}^{q} b_j - \sum_{k=1}^{p} f_{kp} \]  \hspace{1cm} (2.6)
2.5 EXAMPLES OF MOBILITY CALCULATION OF SOME MECHANISMS USING THE TRIZ METHOD

For the mechanism shown in Fig. 2.1, its mobility will be calculated using the previous procedure.

The fixed element is segmented into two parts.

![Figure 2.1](image1)

Let’s suppose that all the elements are disjoined and become free in space, except one. Only one segmented frame remains fixed, the second becomes mobile (Fig. 2.2).

![Figure 2.2](image2)

After segmentation and fictional motion in space (or in plane) the number of temporarily mobile elements becomes equal to the number of kinematic joints, four.

In this phase, the number of degrees of freedom of the
system is $6 \cdot 4$, if it is considered a spatial movement, or $3 \cdot 4$, for a planar movement.

We rejoin the elements by rotational joints of V class, including the temporarily segmented frame (Fig. 2.3) and the constraints of the joints are eliminated $5 \cdot 4$ and $2 \cdot 4$ respectively.

![Figure 2.3]

The extreme element (0) of the open chain has the spatiality three: $Rx$, $Ty$, $Tz$ (whether for a spatial or a planar movement, too).

To compose the mechanism (Fig. 2.1), three degrees of freedom will be eliminated.

If we calculate the mobility of the mechanism by using Eq. (2.5), for a spatial temporary movement, we obtain the mobility 1 (Eq. (2.7)), and for a planar temporary movement we obtain the same result (Eq. (2.8)).

$$M = 6m - 5 \cdot p - b_1 = 6 \cdot 4 - 5 \cdot 4 - 3 = 1 \quad (2.7)$$
$$M = 3m - 2 \cdot p - b_1 = 3 \cdot 4 - 2 \cdot 4 - 3 = 1 \quad (2.8)$$

For the planar mechanism with two closed chains (Fig. 2.4), because three elements are coupling to the frame by simple joints, the frame will be segmented into three parts, so that the number of temporarily mobile elements be equal to the number of kinematic joints, 7.
In the complex joint $C$, between the temporarily open chain 4-5-0 and the closed chain 0-1-2-3-0, we can suppose that there exists one fictive element, 6 (Fig. 2.5).

We analyse the input movements in the open chain 4-5-0, which are determined by the closed chain 0-1-2-6-3-0. They are equal to the spatiality of the fictive platform element 6, integrated only into the previously assembled loop, 0-1-2-6-3-0.

This spatiality is obtained by intersecting the spatiality of the open chain 0-1-2-6 with the spatiality of the open kinematic chain 0-3-6; so:

$$(Rx, Ty, Tz) \cap (Rx, Ty(Tz)) = (Rx, Ty(Tz))$$ (2.9)

Because the element 6 has insignificant dimensions and the axis of rotation of the joint $C2$ is parallel to the axis $x$, there will be no input movement provided by the real closed chain 0-1-2-3-0, except $Ty(Tz)$. 

25
The spatiality of the extreme segmented frame in the open kinematic chain 4-5-0 attached to the previous real closed chain 0-1-2-3-0 (Fig. 2.5) is determined by the input movement $T_y(T_z)$ and by the relative movements in the open chain 4-5-0; it is equal to 3 ($T_y$, $T_z$, $R_x$); that means $b_2=3$. The mobility will be calculated by using Eq. (2.6).

$$M = \sum_{i=1}^{7} f_i - b_1 - \sum_{j=2}^{2} b_j - \sum_{k=1}^{7} f_{kp} = 7 - 3 - 3 - 0 = 1 \quad (2.10)$$

For the mechanism with two closed loops (Fig. 2.6), the frame and the mobile ternary link 3 will be segmented, each of them into two parts, so that the number of temporarily mobile elements be equal to the number of kinematic joints, 7 (Fig. 2.7).
The two closed loops will be rejoined, following the previous principles; the temporarily segmented element 3 must have the same direction and a common point with the initial segment 3, at a given moment.

The element 3 has the spatiality three in the open chain 4-5-3, coupled to the previous loop, 0-1-2-3-0.

The mobility numbers are: $b_1=3$; $b_2=3$.

The mobility of the mechanism will be calculated by using Eq. (2.6):

$$M = \sum_{i=1}^{7} f_i - b_1 - \sum_{j=2}^{7} b_j - \sum_{k=1}^{7} f_{kp} = 7 - 3 - 3 - 0 = 1 \quad (2.11)$$

We consider another mechanism (Fig. 2.8).

![Figure 2.8](image)

There are two joints with $f_1 = f_2 = 1$ and one joint with $f_3 = 2$.

The temporarily segmented frame has 3 degrees of freedom: $Ty$, $Tz$, $Rx$ ($b_1=3$).

$$M = \sum_{i=1}^{3} f_i - b_1 - \sum_{k=1}^{3} f_{kp} = 1 + 2 + 1 - 3 - 0 = 1 \quad (2.12)$$

Fig. 2.9 illustrates the diagram of the Sarrus mechanism.
There are six joints with $f_i = 1$.

We segment the element 2 into two parts.

The extreme element 2 of the open chain associated to the loop has the spatiality 5 ($T_x, T_y, T_z, R_x, R_y$); $b_1 = 5$.

When we rejoin the kinematic chain we observe that each degree of freedom of every joint modifies the movement of the next kinematic element, thus, the number of passive degrees of freedom of the mechanism becomes zero: $\sum_{k=1}^{6} f_{kp} = 0$.

\[ M = \sum_{i=1}^{6} f_i - b_1 - \sum_{k=1}^{6} f_{kp} = 6 - 5 - 0 = 1 \quad (2.13) \]

Pellegrino and al. proposed an alternative form of the Bennett linkage (Fig. 2.10 (b) – the model; Fig. 2.10 (e) – the schematic diagram) with compact folding (Fig. 2.10 (d)) and maximum expansion (Fig. 2.10 (a)) [25].
There are four joints with \( f_1 = 1 \).

The temporarily segmented frame has 3 degrees of freedom: \( Rx, Ry, Rz \) \((b1=3)\).
In [24] it was calculated the global mobility ($M=3$) of a three-translation parallel kinematic mechanism (PKM) with the structure shown in Fig. 2.11.

\[
M = \sum_{i=1}^{4} f_i - b_i - \sum_{k=1}^{4} f_{kp} = 4 - 3 - 0 = 1
\]  

(2.14)

A PKM typically consists of a moving platform that is connected to a fixed base by several limbs.

The PKM shown in Fig 2.11 is a symmetrical PKM because there are three limbs of identical architecture.

Symmetry is one of the main advantages of PKMs because it allows their modularity and reduces their cost.

Every limb has one rotational joint $A_i$ with $f=1$ and two cylindrical joints, $B_i$ and $C_i$ with $f=2$ ($i=1, 2, 3$).

\[
\sum_{i=1}^{9} f_i = 1 + 2 + 2 + 1 + 2 + 2 + 1 + 2 + 2 = 15
\]

There are two independent kinematic chains ($q=2$):
We cut twice the frame, because the rank of the frame is three and we obtain the number of the joints equal to the number of the temporally movable elements, 9.

The spatiality of the extreme segmented frame in the open kinematic chain 0-1-2-3-4-5-0 is 6 \((Tx, Ty, Tz, Rx, Ry, Rz)\); that means \(b1=6\).

We analyse the input movements in the open chain 6-7-0, determined by the closed chain 0-1-2-3-4-5-0.

They are equal to the spatiality of the platform element 3, integrated only in the previously assembled loop, 0-1-2-3-4-5-0.

This spatiality is obtained by intersecting the spatiality of the open chain 0-1-2-3 with the spatiality of the open kinematic chain 0-5-4-3; so:

\[
(Rx, Ry, Tx, Ty, Tz) \cap (Ry, Rz, Tx, Ty, Tz) = (Ry, Tx, Ty, Tz) = 6 \quad (2.15)
\]

The spatiality of the extreme segmented frame in the open kinematic chain 6-7-0 attached to the previously closed chain 0-1-2-3-4-5-0 is determined by the input movements \((Ry, Tx, Ty, Tz)\) and by the relative movements in the open chain 6-7-0; it is equal to 6 \((Tx, Ty, Tz, Rx, Ry, Rz)\); that means \(b2=6\).

The mobility will be calculated by using Eq. (2.6):

\[
M = \sum_{i=1}^{9} f_i - b_1 - \sum_{j=2}^{2} bj - \sum_{k=1}^{9} f_{kp} = 15 - 6 - 6 - 0 = 3 \quad (2.16)
\]

In [6] it was calculated the global mobility \((M=3)\) of the parallel Cartesian robotic manipulator CPM (Fig. 2.12), for two independent kinematic chains, by using the formula demonstrated via the theory of linear transformation.

This mechanism has one passive leg (Antonescu P., 2006).

We apply the new concept obtained by using TRIZ method for the calculation of the mobility of this mechanism.
We cut twice the frame, because the rank of the frame is three and we obtain the number of the joints equal to the number of the elements, 12.

There are two independent kinematic chains \( q=2 \):
0-1-2-3-10-6-5-4-0 and 0-4-5-6-10-9-8-7-0.

The segmented-frame connectivity (number of degrees of freedom of the temporarily segmented frame) in open kinematic chain 0-1-2-3-10-6-5-4-0 is 5 (Tx, Ty, Tz, Rx, Rz); that means \( b_1=5 \).

\[ \text{Figure 2.12} \]

The segmented-frame connectivity in the open kinematic chain 10-9-8-7-0 attached to the previous closed chain is 4 (Tx, Ty, Tz, Ry); that means \( b_2=4 \).

When we rejoin the kinematic chains we observe that each degree of freedom of every joint modifies the movement of the
next kinematic element, thus, the number of passive degrees of freedom of the mechanism is zero, \( \sum_{k=1}^{12} f_{kp} = 0 \).

The mobility will be calculated with Eq. (2.6):

\[
M = \sum_{i=1}^{12} f_i - b_1 - \sum_{j=2}^{12} b_j - \sum_{k=1}^{12} f_{kp} = 12 - 5 - 4 - 0 = 3 \quad (2.17)
\]

The mobility number of the closed kinematic chain is the same, in this case, with the segmented-frame connectivity in open kinematic chain 0-1-2-3-10-9-8-7-0.

If we calculate the mobility of the mechanism with one single closed kinematic chain 0-1-2-3-10-6-5-4-0 (only two legs), we obtain the same result, because one leg is passive. The spatiality of the segmented-frame in the open kinematic chain 0-1-2-3-10-6-5-4-0 is 5 (Tx, Ty, Tz, Rx, Rz); that means \( b_1 = 5 \). The number of the temporarily mobile elements is 8.

The mobility will be calculated by using Eq. (2.5):

\[
M = 6m - \sum_{i=1}^{8} c_i - b_1 - \sum_{k=1}^{8} f_{kp} = 6 \cdot 8 - 5 \cdot 8 - 5 - 0 = 3 \quad (2.18)
\]

or by using Eq. (2.6).

\[
M = \sum_{i=1}^{8} f_i - b_1 - \sum_{k=1}^{8} f_{kp} = 8 - 5 - 0 = 3 \quad (2.19)
\]
2.6 CONCLUSIONS

We consider that the TRIZ method can be utilized even in the case of calculation, where it is required elimination of some contradictions.

We complete the signification of the inventive principle 27 (*cheap short-living objects*) with a new one: the operation, only mentally, by simple action upon the objects, for a short time.

We underline that the results referring to the formulae for a quick calculation of the global mobility and the interpretation of the notion *mobility number* were obtained by using the TRIZ method, independently of other methods such as: the one based on the units of single-open-chain, SOC (Yang, Jin et. al., 2002), or the one based on theory of linear transformation (Gogu, 2005).

By using this method, it isn’t necessary to eliminate the passive elements, the passive limbs of the parallel robots, the symmetry from the calculus of mobility of the mechanisms, except the passive degrees of freedom in each joint which do not change the movement of the next element which must be assembled into an open chain.

In our opinion, even if the results are the same, by using TRIZ it is easier to understand a quick calculation of the global mobility of mechanisms.
3 TRIZ APPLIED TO FUNCTION GENERATING MECHANISMS

3.1 INTRODUCTION

This chapter presents the study of the function generating mechanisms with variable links length using the TRIZ method.

The mechanisms with variable links length (belt-mechanisms or rolling-bar mechanisms) are used frequently in technical applications for function generation.

The path, function, and motion generation are three classes of coordinated motion studied with priority in the synthesis literature.

Linkages, cam-follower mechanisms, and gears are usually used for this scope.

The bar mechanisms can generate imposed functions only approximately. If there are $n$ - mobile elements, the curves pass through maximum $2n-1$ precision points, as Hain K. showed [26].

Many systematic studies about them have been done in the last 3 decades (such as: [26, 27, 28, 29, 30, 31]).

In this chapter some applications are presented:

- a function generating mechanism adapted to obtain functions which differ by constants,
- one example which proposes some units of competences in specified technical domain useful in academic education and
- a new model of mechanism with variable links length, obtained by segmentation of the profiled element.
3.2 THE IDENTIFICATION OF SOME TECHNICAL CONTRADICTIONS IN PATH AND FUNCTION GENERATION

The function generation problem between two rotating planar elements is considered.

Being important for future analysis, we have identified the inventive principles recommended by TRIZ, in the field of function generating mechanisms.

A double-crank four-bar-linkage can give a wide variety of functional relationships between its two cranks while both rotate completely.

In this study some technical contradictions are identified, such as:

- To improve the precision of the generated function until absolute precision, but with the ease of operation (in contradiction matrix: *manufacturing precision / ease operation*, 29/33).
- To improve the precision of the generated function until absolute precision, but with the worsening of the device complexity (in the contradiction matrix: *manufacturing precision / device complexity*, 29/36).
- To improve the precision of the generated function until absolute precision, but with the worsening of the length of the moving object (in the contradiction matrix: *manufacturing precision / length of the moving object*, 29/3). The biggest length of the element is considered initial length.
- To improve the area of the moving object, but with the worsening of the volume of the moving object, 5/7.

For the 29/33 technical contradiction, the matrix recommends [2]: 1 (*segmentation*), 32 (*color changes*), 35 (*parameter changes*), and 23 (*feedback*), as inventive principles.
For the 29/36 technical contradiction, the matrix recommends [2]: 26 (copying), 2 (taking out) and 18 (mechanical vibration), as inventive principles.

For the 29/3 technical contradiction, the matrix recommends [2]: 10 (preliminary action), 28 (mechanical substitution), 29 (pneumatic and hydraulics) and 37 (thermal expansion), as inventive principles.
Principle 28 is the *mechanics substitution* [32]:
- to replace a mechanical means with a sensory means;
- to use electric, magnetic, and electromagnetic fields to interact with the object;
- to change from static to movable fields, from unstructured fields to those having structure;
- to use fields in conjunction with field-activated (e.g. ferromagnetic) particles.

Referring to this principle - 28, despite the advances in electronics and electric hardware and software, mechanically coordinated motion cannot be eliminated in many practical applications. Low cost, reduction in weight, consolidation of parts and improved reliability are important advantages of mechanically controlled machines [33].

For the 5/7 technical contradiction, the matrix recommends [2]: 7 (*nested doll*), 14 (*spheroidality - curvature*), 17 (*another dimension*), 4 (*asymmetry*).
For obtaining rolling-bar mechanisms, three previous contradictions: 29/33, 29/36, 29/3, were unified.

In order to reproduce a wished curve in plane with absolute precision, but with the previous restrictions, the inventive principles: taking out- 2, spheroidality-curvature – 14, and preliminary action – 10, were used.

In order to realize a big area described by a point marked on one mobile element of the mechanism, but with the worsening of the volume described by the moving object, the inventive principles: nested doll – 7, spheroidality – curvature – 14, asymmetry - 4, were utilized.

The inventive principle taking out separates only a property of the changed joint: the number of degrees of freedom (one) and the type of the contact was changed, using at least one superior kinematic joint.

Because we desire to generate an imposed function or path, it is necessary that a point marked on an element follows any point of one curve, so that the lengths of some elements become variable. But it is difficult to coordinate different mechanisms with constant lengths, and the device is complex. It was used the principle spheroidality-curvature: a profiled element defined by a given function was constructed, instead of bar elements and periodic action.

The second element of the superior kinematic pair will be with variable length: a bar or a belt/band/cable.

In the case of a bar, the inventive principles: taking out, preliminary action, and spheroidality – curvature, were applied.

In the case of a belt/band/cable, the inventive principles: nested doll – 7, spheroidality – curvature – 14, asymmetry - 4, and preliminary action allow that a long inflexible object to become flexible and adaptive.

These mechanisms realize elements with variable length during the kinematic cycle of the mechanism.
A band mechanism, ‘as some mechanical contrivance that employs a figuratively inextensible flexible element to transmit force and motion from one principal member to another, usually with winding and unwinding without slippage being used on at least one end of the flexible element, or band’, was defined [27].

Several features of the band mechanism recommend it for function generation, such as: controllable backlash, low inertia, and theoretical accuracy.

The Fig. 3.1 shows a mechanism with cable and one rigid element with Archimede’s spiral profile.

Figure 3.1

First contradiction, in this problem, appears between the cognitive field and the visual field, because it is not so easy to understand the relative motion of one body with respect to the other, if the observer is mobile with respect to both. This contradiction may be eliminated by using the principle the other way round, i.e. to utilize the principle of inverse movement.

For band mechanisms, a simple inversion of the movement with respect to the origin of one rotating element, fixing one of the rotating members, gives a configuration more amenable to analysis.
3.3 A FUNCTION GENERATING MECHANISM ADAPTED FOR OBTAINING FUNCTIONS WHICH DIFFER BY CONSTANTS

The experimental mechanism shown in Fig. 3.2, from a scheme of a six-bar function generating mechanism of centroidal type [31] was inspired.

Figure 3.2

The motion can be transmitted only if the force of the spring tensions the cable.

If the flexible element and the circular rigid element of the mechanism are eliminated, a rigid element mechanism with two driver elements is obtained. The positions of the drivers can be coordinated, but the same movement for the crank-elements of the mechanism with a single driver and variable links length can be obtained.

To generate the functions: \( \psi = \psi(\phi) - C \) (where: \( \phi \) and \( \psi \) are the angles of the cranks during the rotation, and \( C \) are constants) means to generate equidistant curves. For that it is necessary to eliminate the technical contradiction: *improve the area of the moving object*, but with *the ease of manufacture* (in
the contradiction matrix: *area of the moving object/ease of manufacturing, 5/32*).

For the 5/32 technical contradiction, the matrix recommends [2]: 13 (*the other way round*), 1 (*segmentation*), 26 (*copying*) and 24 (*intermediary*), as inventive principles.

The inventive principle 1 is *segmentation* [32]:
- To divide an object into independent parts.
- To make an object easy to disassemble.
- To increase the degree of fragmentation or segmentation.

But, in this case, the principle 1- *segmentation* is:
- To divide a period of action into independent parts (period of time for the preliminary action and period for generating functions) and
  - To action only upon a part of the assembly (two linkages: the profiled element and the driver element).

The inventive principle *the other way round* - 13, upon profiled fixed element and driver element was applied: the driver element (*AB*) rests fixed in a preliminary period of time and the profiled element is rotated.

The constant lengths of the elements, the generating function - $\psi = \psi(\phi)$, the starting positions - $\phi_0$, $\psi_0$ (Fig. 3.3), and the constant $C$ are known.

The problem is to synthesize the profile element that is suitable for using in the band mechanism and to calculate the $\alpha$ angle of rotation of the profiled element.

The point $C_0$ on the end of the flexible element describes a $\Gamma$ path (Fig. 3.3) if the mechanism has a spring (Fig. 3.2).

The $\Gamma$ curve $(x = f(\phi); y = f(\phi))$, using the complex number representation by the known data is obtained.

The $\Gamma$ curve is the involute of the profiled element (the evolute). The evolute $(X = f(\phi); Y = f(\phi))$ is determined with Eqs. (3.1).
The radius of curvature, \( L \), in point \((x, y)\) on \( \Gamma \) curve, with Eq. (3.2) is calculated.

\[
X(\varphi) = x - \frac{y' (x'^2 + y'^2)}{x'y'' - x'y'}, \\
Y(\varphi) = y + \frac{x' (x'^2 + y'^2)}{x'y'' - x'y'},
\]

\[ (3.1) \]

For \( \varphi_0 \) and \( \psi_0 \) input data, the point \((x_0, y_0)\) on \( \Gamma \) curve, the centre of curvature \((X_0, Y_0)\) on the evolute of \( \Gamma \) curve, and the radius of curvature \( L_0 \) are calculated.
For obtaining a new function - $\psi = \psi(\varphi) - C$, and $\Gamma_l$ path, with the same mechanism, the starting position $\varphi_0$ rests the same, and the second starting position is $\psi_0 - C$.

The parametric equations of $\Gamma_l$ curve ($\Gamma$ and $\Gamma_l$ are equidistant curves) are determined with complex number representation, but the parametric equations of the evolute are the same: $X = f(\varphi); Y = f(\varphi)$.

For $\psi = \psi(\varphi) - C$ function, obtained by rotating the profiled element with $\alpha$ angle, the point $(x_1, y_1)$ on $\Gamma_l$ curve, for input data $(\varphi_0, \psi_0 - C)$ is determined.

The centre of curvature $(X_1, Y_1)$ on the evolute, and the radius of curvature $L_1$, in point $(x_1, y_1)$, are calculated.

The $s_1$ length of the arch, between $(X_0, Y_0)$ and $(X_1, Y_1)$, with Eq. (3.3) is calculated.

$$s_1 = \int_{X_0}^{X_1} \sqrt{1+Y'^2} \, dX$$

(3.3)

For obtaining $\psi = \psi(\varphi) - C$ function, the angle of rotation of one circular element, with $r$ radius, with Eq. (3.4) is calculated.

$$\alpha = \frac{L_0 - L_1 + s_1}{r}$$

(3.4)
3.4 EXAMPLE OF UTILISATION OF THE TRIZ METHOD IN ACADEMIC EDUCATION

This study and the experimental mechanism (Fig. 3.2) are useful for the modeling and practical generation of equidistant involutes, of the path contact and the construction of the mating profile useful in Computer Academic Education.

We suggest to university and college students (but not only) that they think critically, practice insight and group learning, for helping them to solve complex problems in technique.

The teachers use the most appropriate methods or strategies of teaching at the undergraduate and graduate seminars for calculation, modelling and practical generation of involute teeth, path of contact and mating profile, following the psychological contents of learning: psychomotor, cognitive and affective [34].

We suggest some competences in a specified technical domain, which are presented below.

The activity is student centred but the interaction is maximal.

- **Unit of competence no. 1**

  To utilize and transpose the mathematical apparatus into a program for the calculation and modelling of a planar gear with involute teeth.

  **The conditions to verify the student behaviour**

  It was created a program which calculates the absolute cartesian coordinates of involute profiles and models the gear (ANNEXE).

  The students have the possibility to utilize the computers, and the results of MAPLE program which was realized (Fig. 3.4 and Fig. 3.5).

  **Competence no. 1.1**
To utilize the notions of evolvent and evolute, various possibilities for the generation of an involute profile, involute function and gear relationships into algorithms.

The wished observable student behaviour

We consider a curve defined by parametric equations: \( x = x(t), \ y = y(t) \); in each point of the curve it may be defined the tangent and the normal. Each of them forms a family of lines depending on parameter \( t \), when the current point describes the curve.

The family of the tangents generates the curve itself, as envelope.

The normal family to the given curve will generate a new curve, which is named evolute of the initial curve.

In conclusion, the evolute of a planar curve is generated as an envelope of its normals.

The points of evolute curve are centres of curvature in the points of evolvent curve.

The curve named involute is the evolvent of a circle, named base circle.

The involutes are generated by the points of a generating line which rolls on the base circle.
There are other possibilities for generating of the involute profile: as envelope with tangent as cutting edge, rolling on base circle; as envelope with tangent as cutting edge, rolling on rolling circle; as envelope of the mating involute profile, rolling on rolling circle; as path described by starting point of a logarithmic spiral, rolling inside and outside of rolling circle.

The Cartesian coordinates of the current point of the right-sided involute profile with Eqs. (3.5) are calculated:

\[
x = r_b \sqrt{1 + \left(\frac{i\theta\pi}{180}\right)^2 \sin\left(\frac{i\theta\pi}{180} - \arctg\frac{i\theta\pi}{180}\right)}
\]

\[
y = r_b \sqrt{1 + \left(\frac{i\theta\pi}{180}\right)^2 \cos\left(\frac{i\theta\pi}{180} - \arctg\frac{i\theta\pi}{180}\right)}
\]

(3.5)

where: \(r_b\) is the radius of the base circle and \(\frac{i\theta\pi}{180} = \alpha_x\).

The Cartesian coordinates of the current point of right-sided involute profile with Eqs. (3.6) are calculated:

\[
x = r_b \sqrt{1 + \left(\frac{i\theta\pi}{180}\right)^2 \sin[\arctg\frac{i\theta\pi}{180} - \frac{i\theta\pi}{180} + 2(tg\frac{a_0\pi}{180} - \frac{a_0\pi}{180}) + \frac{2s_d}{d}]}
\]

\[
y = r_b \sqrt{1 + \left(\frac{i\theta\pi}{180}\right)^2 \cos[\arctg\frac{i\theta\pi}{180} - \frac{i\theta\pi}{180} + 2(tg\frac{a_0\pi}{180} - \frac{a_0\pi}{180}) + \frac{2s_d}{d}]}
\]

(3.6)

where: \(s_d\) is the tooth thickness on the pitch circle, \(d\) is the pitch diameter, and \(\alpha_0\) is the pressure angle of generation.
To obtain the coordinates of the intersection point between the left-sided involute profile and the addendum circle Eqs. (3.7) uses:

\[
x = r_e \sin\left(\sqrt{\frac{r_e^2 - r_b^2}{r_b}} - \arctg\frac{\sqrt{r_e^2 - r_b^2}}{r_b}\right) + x_C
\]

\[
y = r_e \cos\left(\sqrt{\frac{r_e^2 - r_b^2}{r_b}} - \arctg\frac{\sqrt{r_e^2 - r_b^2}}{r_b}\right) + y_C
\]  

(3.7)

where: \(x_C, y_C\) are the cartesian coordinates of the centre of the gear and \(r_e\) is the radius of the addendum circle of the gear.

To obtain the coordinates of the intersection point between the right-sided involute profile and the addendum circle Eqs. (3.8) uses:

\[
x = r_e \sin[2(tg\alpha_0 - \alpha_0) + \frac{2s_d}{d} - \sqrt{\frac{r_e^2 - r_b^2}{r_b}} - \arctg\frac{\sqrt{r_e^2 - r_b^2}}{r_b}] + x_C
\]

\[
y = r_e \cos[2(tg\alpha_0 - \alpha_0) + \frac{2s_d}{d} - \sqrt{\frac{r_e^2 - r_b^2}{r_b}} - \arctg\frac{\sqrt{r_e^2 - r_b^2}}{r_b}] + y_C
\]  

(3.8)

The conditions to verify the behaviour of the students

If the students can’t realize a complete algorithm, the teacher will present the algorithm for the calculus of the
coordinates of one involute tooth and tooth modeling (Fig. 3.4).

**Competence no. 1.2**
To transpose the algorithms into MAPLE programs.

*The wished observable student behaviour*
To form a combative logical thinking of the students for technique.

To calculate the coordinates of the involute teeth points with a program.

The coordinates of intersection points between the right-sided involute profile, the left-sided involute profile and the addendum circle may be calculated with the instruction `solve` in MAPLE program, writing the equations of the addendum circle and the equation of involute profiles, too.

The computational drawing of the gear.

*The conditions to verify the student behaviour*
If it is necessary, the teacher presents one program for the calculus of the coordinates of one involute tooth and tooth modeling.

The students have the possibility to utilize computers.

• **Unit of competence no. 2**
The students compare the obtained programs.

They choose the optimal solution from among the solutions presented by students.

*The wished observable student behaviour*
It will be developed the creativity of the students by using the Brainstorming method, in order to obtain a critical thinking.

*The conditions to verify the behavior of the students*

The students present their own results (modified program) obtained at the competence no. 1.2.

They have the possibility to run and modify the programmes operating the computers.

• **Unit of competence no. 3**
To determine for the given profile the path of contact and the mating tooth profile, point by point.

The wished observable student behaviour

Using Reuleaux method it can be determined the path of contact and the mating tooth profile, point by point, for a given profile.

For each point $E_1$ of the given tooth profile there is a point of the path of contact and a particular point $E_2$ of the mating profile.

The path of contact is the locus of all the points of contact of a pair of tooth profiles with respect to the reference system.

If one profile and the two rolling circles are given, we can construct point by point the path of contact and the mating profile, using the law of gearing.

It will be obtained the practical model of the gear mechanism by students (Fig. 3.6).

- Unit of competence no. 4
  
  To obtain the concordance between theory and practice verifying the process of gearing, and the law of gearing.

  The wished observable student behaviour

  To observe the variation of the point of contact between two conjugated teeth during the gearing process in the model mechanism.

  To verify the curvature of the path of contact described in the model mechanism.

  To verify the constancy of the ratio of transmission by measurements of the rotation angles of the gears in different moments of time, in the model mechanism.

  The conditions to verify the behaviour of the students.

  The practical model of the gear mechanism realized by students, or by teacher, if the students couldn’t realize it (Fig. 3.6).
Unit of competence no. 5

To generate the equidistant involutes using the model mechanism with variable length of flexible element.

The wished observable student behaviour

To generate an imposed function, or a wished trajectory it will be introduced in the structure of the mechanism a superior joint, using a cable that is rolling on a profiled element. This mechanism realizes variable length elements during the kinematic cycle of the mechanism.

For the mechanism represented in Fig. 3.2 the motion can be transmitted only if a force of a spring tensions the cable. If the flexible element and the circular rigid element of the mechanism are eliminated, it will be obtained a rigid element mechanism with two driver elements.

It can be coordinated the positions of the drivers, but we can obtain the same movement for the elements of the mechanism with a single driver if the mechanism has a circular rigid element and a cable that is rolling on it (Fig. 3.2).

If we want to generate equidistant evolvent curves, we can rotate the circular element around a fixed point. When we
rotate the circular rigid element with an imposed angle, the length of the cable and the initial positions of the elements 1 and 2 \((\varphi_0, \psi_0)\) are modified. If the initial position of element 1 \((\varphi_0)\) is fixed and we rotate the circular element, will be modified only the initial position of element 2 \((\psi_0)\). By modifying the initial position of the element 2 we obtain functions which differ by a constant \((\psi(\varphi) + \text{const})\).

The conditions to verify the student behaviour

Papers, practical model of the mechanism (Fig. 3.2)

Supplementary units of competence for graduate student projects:

- **Unit of competence**
  
  To obtain the concordance between theory and computational modeling by verifying the process of gearing, and the law of gearing.

  The wished observable student behaviour

  To rotate with MAPLE program one gear and its conjugate gear. To observe the variation of the point of contact between two conjugated teeth during the gearing process in the computational model. To observe the path of contact described in the computational model.

  To obtain the angles of rotation of the gears at different moments of time and to calculate the ratio of transmission.

- **Unit of competence**

  To calculate the angle of rotation of the circular element of the mechanism with variable lengths of the flexible element which generate equidistant involutes.
3.5 TRIZ APPLIED TO ELIMINATING SOME PHYSICAL CONSTRAINTS IN FUNCTION GENERATING MECHANISMS

Another important objective of the study was to utilize the TRIZ method to eliminate some physical constraints indicated by McPhare (1966): the interference of the profiles, the interference between cable and profile caused by changing the sign of the radius of curvature.

In paper [27] the author investigated the physical constraints on band mechanisms and the application of these constraints to the design equations:

- the band must be unique;
- the length of the band must not go to infinity;
- the band in last positions must not interfere with the profile of earlier positions;
- in a bi-directional mechanism (requiring two bands and two profiles), the two profiles must not interfere.

We can utilize TRIZ for obtaining complex desired functions, even though the profiles interfere, and there are inflexion points on profiles.

This case study proposes a new concept for generating complex curves with function generating mechanisms with variable link length, based on the TRIZ methodology.

To obtain complex desired functions, the 35/33 contradiction (adaptability/ease of operation) has been eliminated, by using inventive principles:

- **dynamics (15):** the reference element has been divided into different plates, with possibility of changing the rotational joint (a particular case: equidecomposable figures);

- **segmentation (I) + discarding and recovering (34):** profiled element has been divided into different parts which are now fixed on the little plates and some parts are discarded.
Periodic action by cable of the profiled elements is possible by changing the position of the rotational joints, by segmentation of the profiled element, and by the forms of the little plates (on which the profiled elements are fixed) which eliminate some relative movements.

One example is presented below.

The delightful snapshot presented by Steinhaus in 1939 [35] uses two echidecomposable figures, with four little plates: 1, 2, 3, 4 (Fig. 3.7).

![Figure 3.7](image)

On each plate another element is fixed, with different profile.

It can take action with only one motor on the plate no. 4, actuating through cable the mechanism.

Fig. 3.8 depicts the experimental model of this mechanism actuating through one cable reeled on two reels.

For different laws of movement of little plates, the profiled elements will be designed.

Thus, a variable complex mechanism, with variable links length was obtained.
In conclusion, the TRIZ method can be used in Computer Academic Education, to establish some unit of competences and to eliminate some constraints.
4 CREATIVITY IN BIONICS

4.1 INTRODUCTION

This chapter presents remarks on creativity in the field of bionics on the author’s opinion.

The steps of the strategy in the process of scientific creation used in bionics, some applications in robotics and academic education are exposed.

Experimental analysis, thought experiments, visual analogy (image representation and relationships, especially mathematical and causal relationships), inventive principles recommended by TRIZ, maintenance of the idea in long-term-memory and intensive attention on it, cognitive historical analysis, were utilized in the process of creativity.

Several structural legged robots were developed, more or less intricate, with movement in plane or in space, inspired from the movement of thousand-legged worms and caterpillars.

The science that uses analogies from biology or botany for solving new engineering problems is named bionics.

Continuity of the authors knowledge of results of previous investigations is useful in many studies.

The history of inventions proves that the maintenance of an idea in long-term memory and intensive attention on it, have had an important role in creativity [36-38]; experimental analysis and analogy are usual tools for it, too.

The visual image plays a central role in the earlier phase, but analogical reasoning can only give probable conclusions.

Thought experiments and calculations are able to verify the presumptions offered by analogies.

Other methods, such as TRIZ, can be used to eliminate the technical contradictions and obtain the final target.

The thousand-legged worms and the caterpillar were selected for this study, the reason being their movement which
is so interesting because of their capabilities. For example, the narrow spaces do not raise any problems for them, and complex spatial curves can be easily followed.

The principal features of their locomotion were applied to obtain functional mini-robots, but with few actuators and without intricate structures.

4.2 DESCRIPTION OF THE PROCESS OF CREATIVITY IN BIONICS

It is amazing to discover the algorithms of our mind during creative thinking, the steps in the process of creativity, but it is better to organize the process in advance. In this study, the models were initially created, all the possible analyses were made, and finally creativity techniques were explored.

Different questions referring to the creativity in bionics were asked:

- What is the role of image representation in bionics?
- What is the influence of internal or external strain in the process of creativity?
- What is the role of time upon the last activated remembrance in the process of analogy?
- What is the influence of the intensity of the information stored in the long-term memory in analogical process?
- If different steps in the process of scientific creation are followed, or different creativity techniques studied and presented by others are utilized, will the result of the study in the same domain, for the same problem, be much better, or the same?

The steps forming the strategy used in the study are:

A. Morphological analysis of the living creature: the animal.
B. Analysis of locomotion in different directions and on different substrata.
C. Brief representation of the initial source – the scheme source.
D. Process of retrieval and elaboration of an analogical model – an enhanced source.
E. Mapping and transfer between the enhanced source and the probable target.
F. Evaluation
G. Elimination of the contradictions using the TRIZ method if the probable target does not agree with the wished target.
H. The internal or external strain and the comparison by analogy with possible different targets of other inventors.
Each of them will be discussed in detail in the following sections.
4.3 STRATEGY

A. Morphological Analysis of a Living Creature: The Animal

It was realised a minute morphological analysis, even if in the future will make a general image representation, because the relationships determined by morphology will be indispensable.

Two examples are presented, a caterpillar (*Lepidoptera* – Fig. 4.1) and a millipede (*Litobius Forficatus* – Fig. 4.2).

The complete morphological analysis is made in [39].

A1. Lepidoptera

For the morphological analysis of the Lepidopterous larva the microscope was used.

It has no skeleton. The body has three thoracic and nine abdominal segments with eight pairs of legs. The thorax bears three pairs of legs on the segments 1-3 and the abdomen bears five pairs of prolegs on the segments 6-9 and 12.

Each thorax leg has five segments connected with rotational joints, except the joint between the body and the first segment that is a spherical joint.

The prolegs are conical, retractile and have hooks on the apex (Fig. 4.2).
A2. *Litobius forficatus*

The millipede’s body has jointed segments and the exoskeleton of each segment has two parts: the tergum - dorsally placed, and the sternum - ventrally placed, moved by internal muscles.
The experimental morphological analysis of some samples of carnivorous millipedes with the same dimensions and with different dimensions of the tergum was made.

Between the segments, the exoskeleton remains thin and flexible, making a pleural membrane, moved by intrinsic muscles.

The form of tergum and the pleural membrane introduce performant redundant movements.

In Fig. 4.4 the planar surface of the tergum is represented with hatch-line and the bulging surface of the tergum without hatches.

![Figure 4.4](image)

The narrow tergum has two sharp plane hinder prolongations, placed laterally, which can slide and turn over the previous plane surfaces of the broad tergum.

The narrow tergum can leave the plane surface of the broad tergum and the pleural membrane maintains the connection.

This pleural membrane allows three rotations and three translations.

The rotation in the plane of locomotion is limited, but the pleural membrane allows a greater rotation in a perpendicular plane on it, which contains the longitudinal axis of the millipede.
The previous surface of the narrow tergum is a bulging surface and the broad tergum has a hinder plane surface.

Each segment has a pair of appendages placed ventrolaterally and consists of a series of articles, characteristics common insects (Fig. 4.5).

![Figure 4.5](image)

The elements of appendages are jointed and can slide ones into anothers.

The coxis forms a spherical joint with the segment of the body.
B. Analysis of Locomotion in Different Directions, on Different Substrata

The experiments have great importance in verifying the presumptions offered by analogies.

The experimental research incorporates a high degree of control over the variables during different processes.

This control enables the experimenter to establish causal relationships between the independent and dependent variables.

But these experiments aren’t enough; if you want to change something old and create something new, you have to give priority to thought experiments, to combine them.

‘The original thought experiment is the construction of a mental model by the scientist who imagines a sequence of events.

She or he then uses a narrative form to describe the sequence in order to communicate the experiment to others.’ [40].

For this analysis, experiments and thought experiments may be utilised using some TRIZ inventive principles, like the other way round.

It is necessary to obtain the laws of movement.

If it is not possible at this step, the process will be cycled after step (C), when a scheme-source is finished.

B1. An application for the principle the other way round, useful in Computer Academic Education

It is presented the animation of a four-jointed elements mechanism which describes a pressed D curve and the principle of opposite movement for designing of stepping mechanisms using the program PASCAL, useful in Computer Academic Education.
Our intention is to obtain the competences of the students because it’s necessary to utilize the same units in the process of evaluation.

- **Unit of competence no. 1**
  To transpose the principle of inverse movement into a programme of animation for a planar mechanism

  *The conditions to verify the behaviour of the students*
  We use a program which realizes the animation of a four-jointed elements mechanism which describes a pressed \( D \) curve, and the animation of the same mechanism using the principle of inverse movement.
  The students have the possibility to utilize computers.

  *Competence no. 1.1*
  To describe the motion of the elements of the mechanism before and after the principle of inverse movement is applied.

  *The wished observable behaviour of the student*
  The point of planar element which describes in the real mechanism an approximate rectilinear trajectory, rests fixed by applying the principle of inverse movement.
  The fixed element in the first mechanism becomes mobile during this operation.
  It has an opposite motion by comparison with the point with rectilinear motion in the real mechanism and booth have the same modulus of speed.

  *The conditions to verify the behaviour of the students*
  It is presented only the animation for a four-jointed element mechanism that describes a pressed \( D \) curve.
  The students have the possibility to utilize computers.

  *Competence no. 1.2*
  To particularize the program for two opposite positions of the driver element of the real mechanism.

  *Competence no. 1.3*
  To indicate the positions of bit end for opposite positions of the driver element of real mechanism.
The wished observable behaviour of student

The two bit ends there are on the two different parts of the curve so:
- one of them is on the rectilinear part of trajectory
- the other is on the curved part of the trajectory.

The conditions to verify the behaviour of the students

It is presented the program (ANNEXE) which realizes superposition of the mechanism for a finite number of positions of the driver element (Fig. 4.6).

The students have the possibility to modify the existing program.

Figure 4.6

Competence no. 1.4

To verify the transposition of the principle of inverse movement in a program of animation.
The wished observable behaviour of student
To verify the motions of the elements of the mechanism before and after the principle of inverse movement is applied.

The conditions to verify the behaviour of the students.
It is presented the animation of a four-jointed elements mechanism - which describes a pressed $D$ curve - affected by the principle of inverse movement (Fig. 4.7).

The students have the possibility to utilize the computer program.

Figure 4.7

- Unit of competence no. 2
To adapt the four-jointed elements mechanism to obtain a legged mechanism.

The wished observable behaviour of the student
It is considered two four - jointed element mechanisms.
We can attach one element to the bit end of each mechanism so that the free end of the element to be under the level of the fixed element of the real mechanism.
We immobilize the driver elements of the mechanisms in opposite positions.

*The conditions to verify the behaviour of the students*

The students can use their own results (modified program) obtained at the competences no. 1.2 and no. 1.3. They have the possibility to run and modify the program operating computers.

- **Unit of competence no. 3**
  
  To generalize the process of motion for a legged mechanism with two four-jointed elements mechanisms.

  **Competence no. 3.1**
  
  To observe the period of time in which each leg is fixed on the ground.

  *The wished observable behaviour of student*
  
  In the period in which the bit end of the initial mechanism must be on the rectilinear part of the curve, each leg of the legged mechanism is fixed on the ground.

  **Competence no. 3.2**
  
  To observe the behaviour of the initial base in the same period of time.

  *The wished observable behaviour of student*
  
  In this period of time the initial base has an opposite motion comparison with the point with rectilinear motion in the real mechanism and booth have the same modulus of the speed.

  **Competence no. 3.3**
  
  To observe the behaviour of the antiphasis legs in the same period of time.

  *The wished observable behaviour of student*
  
  The antiphasis leg which is on the curved path of the trajectory advances simultaneously with the initial base because it doesn’t touch the ground and it hasn’t relative movement by comparison with initial base.

  **Competence no. 3.4**
  
  To infer from all the study the complete cycle of motion.

*The wished observable behaviour of student*
The leg witch was fixed becomes mobile, the mobile leg becomes fixed and the initial base advances with the same modulus of speed like the speed of the bit end from the real mechanism.

The teacher presents some applications: ’the horse of Cebisev’ and others legged mechanisms with four-jointed elements mechanisms and mechanisms with oscillated slide.

To obtain a critical thinking from the students the teacher proposes to select end points of curve rectilinear portion, because these are necessary for applying the inverse motion principle.

The solutions proposed by students will be discoursed individually or in-group.

Finally, it will be choicen the optimal solution from among the solutions presented by students.
B2. Examples in bionics

For the study of locomotion of caterpillars and millipedes, a video camera was used. Some parts from the images were processed on a computer with multimedia system for reduced speed, moderate speed and for the running of the animals on different curves.

B 2.1. The caterpillar

The elements of caterpillars that assure the locomotion are the thoracic jointed legs, the abdominal elastic legs and segments of the body.

The larva walks by looping the body, the wave going from the hind segments to the thoracic segments.

The movement of the body is intermittent. A half of the body is straight and the other is compressed when the larva walks. The centre of curvature is on the intersection of two pairs on the substratum.

For a speed greater than 14 mm/s, the thoracic legs can be raised successively in the air, from the back to the front, three pairs of legs being hanging in the air at a given moment.

Then, the thoracic legs touch the substratum in inverse order with respect to its rising (Fig. 4.8).

For higher speeds, the loop has a larger radius of curvature, and more pairs of legs are in the air.

These observations were easy enough to obtain.

B 2.2 Litobius forficatus

In the case of the millipede (Litobius forficatus) the situation was different: the priority was given to experiments on glass, where the creative principle the other way round, presented by the TRIZ method, was applied.
Experiments on glass

Initially there was a contradiction between the cognitive field and the visual field: the movement was seen, but the law of movement could not be understood, going forward and going back, the possible positions of the legs, one towards another, the positions between segments and legs, and the positions of the body segments.

In order to eliminate this contradiction the principle the other way round was used, i.e. to utilize the principle of inverse movement through experiments on glass substratum.

Because the coefficient of sliding friction was not great, the millipede does not advance.

With the help of experimental setup (video camera, computer with multimedia system - Movie Machine, microscope), a base of millipede images during the movement, useful for the analysis of the complex locomotion, was created (Fig. 4.9).

I have made many measurements of the angular displacements of the legs with respect to the segments, position of the last segment of the legs, positions of the body segments.
Some angular positions of the selected legs: P1, ..., P12 (Fig. 4.10), with respect to transversal axes of the body segments can be seen in Table 4.1. (unid=unidentified)

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The experiments were useful to determinate the laws of movement. Thus, it was found in Table 4.1 (rows: 9-15; columns: P6-P12) a cyclical law for the direction of rotation of each leg of *Litobius Forficatus* for a usual type of locomotion: the movement on a straight line. It was observed the laws of the movement of the legs with respect to the body.
Figure 4.10

Step 1
$t=0\, s$

Step 2
$t=0.04\, s$

Step 3
$t=0.08\, s$

Step 4
$t=0.12\, s$
Figure 4.10

Step 5
$t=0.16 \, s$

Step 6
$t=0.2 \, s$

Step 7
$t=0.24 \, s$

Step 8
$t=0.28 \, s$
Figure 4.10

Step 9
$t=0.32\, s$

Step 10
$t=0.36\, s$

Step 11
$t=0.4\, s$

Step 12
$t=0.44\, s$
Figure 4.10

Step 13
$t=0.48 \, s$

Step 14
$t=0.52 \, s$

Step 15
$t=0.56 \, s$

Step 16
$t=0.6 \, s$
Figure 4.10

Step 17
$t=0.64\ s$

Step 18
$t=0.68\ s$

Step 19
$t=0.72\ s$

Step 20
$t=0.76\ s$
Figure 4.10

Step 21  
t=0.8 s

Step 22  
t=0.84 s

Step 23  
t=0.88 s

Step 24  
t=0.92 s
Step 25  
$t=0.96\ s$

Step 26  
$t=1\ s$

Step 27  
$t=1.04\ s$

Step 28  
$t=1.08\ s$
The antagonistic sets of muscles of the appendages require that each pair of legs to be in straight line, not quite to be ortho on the axis of the body segment.

The angle of rotation for each pair of legs varies from $45^0$ to $135^0$ and the direction of rotation alternates.

Any two consecutive pairs of legs form an angle of $45^0$ between their axes.

The period of the movement of the legs' wave is at each fifth pair of legs.

At a given moment of time two consecutive pairs of legs are rotating in the same direction, and after two pairs of legs the rotation alternates.

The succession of the leg movement when three legs are intersecting in a centre of curvature is shown in Fig. 4.11.

Using the packet of *Mathematica* programs the functions of the angular displacements, the angular speeds and the angular accelerations were obtained.

The angular speed varies from $400 \, ^0/s$ to $1000 \, ^0/s$.

The angular acceleration varies from $10000 \, ^0/s^2$ to $50000 \, ^0/s^2$.  

80
Going on the background

Positions of the last segment of the legs and angular displacements of the leg pairs (Fig. 4.12) are presented in the table 4.2; the millipede moves on a paper (t = 0 - 0.44 s). All these dates are reported to a system of coordinates fixed on the background.

The diagrams of angular displacements for seven pairs of successive legs are presented (with dates from table 4.2) in Fig. 4.13.

![Figure 4.13](image)

The principle of the inverse movement is: if the final segments of the legs are fixed, the body advances, but the law of action of the muscles is the same.

Using the packet of Mathematica programmes the functions of the angular displacements, the angular speeds and the angular accelerations were obtained. The intervals of time when the legs are fixed on the background were selected.

The functions of some successive legs can be seen below.
Figure 4.12
### Table 4.2

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For the leg P2 (the interval of time: 0,08 s - 0,2 s):
\[ \phi(t) = -394 + 13611.7 t - 170646 t^2 + 947396 t^3 - 1.90104 \times 10^6 t^4 \]
\[ \phi'(t) = 13611.7 - 341292 t + 2.84219 \times 10^6 t^2 - 7.60417 \times 10^6 t^3 \]
\[ \phi''(t) = -341292 + 5.68438 \times 10^6 t - 2.28125 \times 10^7 t^2 \]
For the leg P3 (the interval of time: 0,035 s - 0,13 s):
\[ \phi(t) = 24.9201 + 542.673 t - 19737.3 t^2 - 1.15411 \times 10^6 t^3 \]
\[ \phi'(t) = 542.673 - 39474.5 t + 839396 t^2 - 4.61644 \times 10^6 t^3 \]
\[ \phi''(t) = -39474.5 + 1.67879 \times 10^6 t - 1.38493 \times 10^7 t^2 \]
For the leg P4 (the interval of time: 0,16 s - 0,28 s):
\[ \phi(t) = 652.108 - 8276.34 t + 30776 t^2 - 23052.9 t^3 - 23052.9 t^4 \]
\[ -18030.5 t^5 - 8442.69 t^6 - 3418.15 t^7 \]
\[ \phi'(t) = -8276.34 + 61552 t - 69158.7 t^2 - 117761 t^3 - 90152.6 t^4 \]
\[ -50656.1 t^5 - 23927 t^6 \]
\[ \phi''(t) = 61552 - 138317 t - 353282 t^2 - 360611 t^3 - 253281 t^4 \]
\[ -143562 t^5 \]
For the leg P5 (the interval of time: 0,039 s - 0,29 s):
\[ \phi(t) = 665.473 - 58187.6 t + 1.95698 \times 10^6 t^2 - 3.40783 \times 10^7 t^3 + 3.40674 \times 10^8 t^4 - 2.01999 \times 10^9 t^5 + 7.0013 \times 10^9 t^6 - 1.30817 \times 10^{10} t^7 + 1.01658 \times 10^{10} t^8 \]
\[ \phi'(t) = -58187.6 + 3.91395 \times 10^6 t - 1.02235 \times 10^8 t^2 + 1.36269 \times 10^9 t^3 - 1.00999 \times 10^9 t^4 + 4.20078 \times 10^{10} t^5 - 9.15718 \times 10^{10} t^6 + 8.13263 \times 10^{10} t^7 \]
\[ \phi''(t) = 3.91395 \times 10^6 - 2.0447 \times 10^8 t + 4.08808 \times 10^9 t^2 - 4.03997 \times 10^{10} t^3 + 2.10039 \times 10^{11} t^4 - 5.49431 \times 10^{11} t^5 + 5.69284 \times 10^{11} t^6 \]

The angular speed varies from 400000/s to 10000000/s.
The angular acceleration varies from 10000000/s^2 to 5000000000/s^2.

Positions of the centres of mass of body segments (Fig. 4.12) are presented in the table 4.3.
Table 4.3

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Using *Mathematica* packet of programs, the functions $x(t)$, $y(t)$, $x'(t)$, $y'(t)$, $x''(t)$, $y''(t)$, of the centre of mass of body segments were obtained.

The maximum speed of the centre of mass of body segments is $35 \text{ mm/s}$ in the direction of $x$ axis and $10 \text{ mm/s}$ in the direction of $y$ axis.

The maximum acceleration of the centre of mass of body segments is $500 \text{ mm/s}^2$.

These two experiments (on glass and on background) revealed the independent movement of the body segments and the movement of the appendages with respect to the body.

The relative position of the legs and the kind of action of the joints are the same as those presented in the movement on glass, but the legs touch the background.

The succession of the legs that are in contact with the background are presented below (L=left, R=right).

For the going forward, following a curve in plane with a straight axis, the support is provided by the following legs: $L_1, R_2, R_3, L_4, L_5$, altering with $L_1, L_2, R_3, R_4, L_5$, altering with $R_1, L_2, L_3, R_4, R_5$, altering with $R_1, R_2, L_3, L_4, R_5$.

For the going back, following a curve in plane with a straight axis, the support is provided by the following legs: $R_1, L_2, L_3, R_4, R_5$, altering with $R_1, L_2, L_3, L_4, R_5$, altering with $L_1, R_2, R_3, L_4, L_5$, altering with $L_1, L_2, R_3, R_4, L_5$.

For the going forward, following a curve in plane with a curve axis, the support is provided by the following legs: $L_1, L_2, R_3, R_4, R_5$, altering with $L_1, L_2, R_3, R_4, R_5$, altering with $L_1, L_2, L_3, L_4, L_5$, altering with $R_1, L_2, L_3, L_4, L_5$, altering with $R_1, R_2, L_3, L_4, L_5$, altering with $L_1, R_2, R_3, L_4, L_5$. 

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It was concluded the *law for straight movement*: the legs that are on the curve of the body, at a given moment, from an inflexion point to the next, exclusively, which are intersecting in the centre of curvature, touch the substratum, and the corresponding legs in the same pairs are lifted. This feature is also valid for curves with a greater radius of curvature. The number of the legs is proportional to the dimension of the radius.

For the *going back*, the legs that are on the curve of the body, at a given moment, from an inflexion point to the next, exclusively, which are intersecting in the centre of curvature, are lifted, and the corresponding legs in the same pairs touch the substratum. The action modality of the muscles is the same for the forward walking, only the points of contact with the substratum are others.

For *traveling on a curve* all the elements that are in the centre of curvature touch the substratum with the help of sliding or rotational joints and all kinematic chains in this curve are inactive until the mechanism changes the direction. The passive chains have a rotational movement around the centre of curvature, until the first element reaches the limited position (at $45^0$ in the direction of travel). After this, each element follows the previous law of movement.
C. Brief Representation of the Initial Source – The Scheme Source

This step is considered by the author to be very important: the realization of a scheme of the source according to the principal purposes of analysis; by discarding irrelevant relationships in the initial source and storing critical ones, a new scheme-source can be obtained. The author considers the visual analogy the basis of scientific creation in bionics.

This first enhanced source - the scheme-source with selected relationships, especially mathematical and causal relationships - will be the new source-model. Both image representation and analogical reasoning must be used for creating new models. Some examples are presented below.

The morphological analysis, the analysis of the movement in different conditions, on different substrata, on different curves, in plane or in space, help at realization of simplified schemes.

Some schemes focus on the specific relationships of the phenomena.

Fig. 4.14 depicts a simplified scheme, with visual similarities with respect to the animal during locomotion.

The same figure, a triangle, was observed between the elements of the ‘body’.

This idea was stored in the memory, because it might be useful later.

This scheme was used for a spatial mechanism [41].

Some geometrical restrictions and relationships which establish the laws for different types of movement, useful to create new planar or spatial mechanisms were added to this scheme.

The positions of the legs and their law of movement in plane were kept, but the form of the body was simplified, using the same allure, like a wave.
The elements: 1, 2, 3, 4, 5 (Fig. 4.14) were reduced to ‘beam’ type elements: 1, 2, 3, 4 (Fig. 4.15).
The elements 1, 2, 3, 4, are midlines in the resulting triangles (Fig. 4.15).

In the case of the movement of Lepidoptera, we store the scheme of some jointed elements in a serial linkage, but with a grate facility for compactness, change of direction and for torsion.
D. Process of Retrieval and Elaboration of an Analogical Model – an Enhanced Source

The process of retrieval and elaboration of an analogical model to develop an enhanced source used the scheme-source which is common in both, the crude and the target domains.

Two examples can be seen below.

For the caterpillar (*Lepidoptera*), some complex structural models (Fig. 4.16 and Fig. 4.17) of walking robots with rigid elements were realized.

But, they were too complicated, with too many actuators, leading to the conclusion that the targets are not acceptable.

This strain influences on our minds.

The base of images of the *Litobius forficatus* was useful to realize the structural models by analogy.

A complex structural model of one walking robot was made and analyzed (Fig. 4.18).
Figure 4.18
E. Mapping and Transfer from the Enhanced Source to the Probable Target

This step continues the process and is completed by evaluation.

Some examples can be seen below.

The specific features of the millipede locomotion were kept, for different types of locomotion creating different stepping mechanisms [41].

The simplified body in different positions in the plane was drawn (Fig. 4.19).

The sustained triangular form (or like a cone) in different positions in plane was observed. Attempts were made to rotate the triangles (or cones) from one position to the next to obtain the desired positions in plane.
And thus, a spatial structural model inspired from these schemes was created.

Fig. 4.20 represents the new structural model of robot *MMS5*.

The structural model has 17 rigid elements, 12 joints of rotation (C, D, E, F, G, H, I, J, M, N, O, P) and 4 cylindrical joints (A, B, K, L).

The elements 1, 2, 3, 4, 5 are cylinders and 10, 11, 12, 13 could be cones or triangles.

The elements 14, 15, 16, 17 can be rotated in the joints N, M, P, O, at different moments.

![Figure 4.20](image)

While it is in plane, the form of the mechanism is the same as the millipede’s body during some periods of the movement.

The cones could have some channels, and some spherical elements can be between the cones and the cylinders.
F. Evaluation

All process is completed by evaluation.

F. 1 Model *MMS5*

The picture of the model MMS5 can be seen in Fig. 4.21.

![Figure 4.21](image)

The mechanism could have different laws of movement in space, according to the kind of action of the leading joints.

But, while it is in-plane, the form of the mechanism is the same as the millipede’s body during some periods of movement.
Having applied thought experiments you can try to realize some experiments to certify your new theory (Fig. 4.22).

Fig. 4.23 and Fig. 4.24 depict the direction of rotation of the elements of the robot, during a complete cycle, for motion from right to left and from left to right, respectively.

![Figure 4.23](image-url)

**Figure 4.23**

![Figure 4.24](image-url)

**Figure 4.24**

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Figure 4.22
I realized the program (ANNEXE) using partitioned matrix algebra ([42]) to calculate:

- the matrices of base change,
- the generalized coordinates,
- the angular speeds,
- the matrix with the partial angular speeds,
- the absolute angular speeds and the absolute accelerations of the kinematical elements,
- the absolute speeds and accelerations of some points of kinematical elements.

Each kinematical element was associated with its CARTESIAN system of coordinates, with base of vectors:

\[ \{ i \} = \{ i_1, i_2, i_3 \}^T. \]

The \( E \) absolute reference was associated with the base of vectors:

\[ \{ i \} = \{ i_1, i_2, i_3 \}^T \]

and the element \( j \) with the \( P \) system.

In general case, the \( E \) system will be rotated three times, until its axes are identical with the axes of \( P \) system (Fig. 4.25).

Because the rotation of the \( E \) system around its three axes with unchanged angles, but following other succession, generates a system with other orientation, it is necessary to be attentive at the forms and known movements of the elements of the mobile system.

For the transformation of the \( E \) system into the \( P \) system, we use Eq. (4.1).

\[
\{ i \} = [E_S^P] \{ \overset{\to}{i}_{0} \}
\]

where \([E_S^P]\) is calculated with Eq. (4.2).

\[
[E_S^P] = [E_2^E] [E_3^E] [E_1^E] [E_S^E]
\]
Considering the element $j$ with respect to the element $k$ and the three angles which give the orientation of the system $R_j$ with respect to the system $R_k$ (which are met in the matrix of base change $J^S_k$) we consider:

$$\{\varphi^k\} = \{q^k\}_R = \{\varphi^k_1, \varphi^k_2, \varphi^k_3\}^T.$$

For a system with $n$ rigid elements joined by rotational links, the generalized coordinates are components of the vectors: $\{q^k\}_R, k = 1, n$; that means $3n$ geometrical parameters, which are noted: $q_1, q_2, ..., q_{3n}$.

The vector of the generalized coordinates is:
\[ \{q\} \equiv \{q\}_R = \{\{q\}_R^1, q_R^2, \ldots, q_R^n\}^T = \{q_1 q_2 \ldots q_{3n}\}^T \]

In the case of this model, MMS5, we can’t rotate all systems in the same previous succession and keep so one single form for the matrix of base change \([JS]^k\], because the knowledge of angles of rotation is very difficult in that succession.

Each system will be rotated first with constant angles around certain axes and finally with variable angle until the system will be transformed into the system of the following element.

The first system in this process will be the absolute reference.

The succession of rotations for the transformation of the systems there is (Fig. 4.26):

- The transformation from the system 0 into the system 1, by rotation around \(z_0\) axis with the angle \(q^0_3\) (this operation isn’t presented in Fig. 4.26); \(q^0_3 = \phi_3^1 t; q^0_1 = q^0_2 = 0\).

- The transformation from the system 1 into the system 2, by rotation around \(y_1\) axis with the angle \(q_2\); \(q_2 = -180 + \phi_2^2 t; q_1 = q_3 = 0\).

- The transformation from the system 2 into the system 3, by rotation around \(z_2\) axis with the angle \(-45^0\); one rotation around \(y_2\) axis with the angle \(q_5\); \(q_5 = \phi_3^3 t; q_6 = -45^0\).

- The transformation from the system 3 into the system 4, by rotation around \(x_3\) axis with the angle \(180^0\); one rotation around \(z_3\) axis with the angle \(225^0\); one rotation around \(y_3\) axis with angle \(q_8\); \(q_8 = \phi_2^4 t; q_7 = 180^0; q_9 = 225^0\).
- the transformation from the system 4 into the system 5, by rotation around $z_4$ axis with the angle $-45^\circ$; one rotation around $y_4$ with the angle $q_{11}$; $q_{11} = \dot{\varphi}_2 t$; $q_{10} = 0^\circ$; $q_{12} = -45^\circ$.

Figure 4.26

The matrices of base change for robot MMS5 are given by relations (4.3).
\[
[0S^1] = \begin{bmatrix}
c_3 & s_3 & 0 \\
-s_3 & c_3 & 0 \\
0 & 0 & 1
\end{bmatrix}; \quad [1S^2] = \begin{bmatrix}
c_2 & 0 & -s_2 \\
0 & 1 & 0 \\
s_2 & 0 & c_2
\end{bmatrix}; \\
[2S^3] = \begin{bmatrix}
c_2c_3 & c_2s_3 & -s_2 \\
-s_3 & c_3 & 0 \\
s_2c_3 & s_2s_3 & c_2
\end{bmatrix}; \\
[3S^4] = \begin{bmatrix}
c_2c_3 & c_2s_3c_1 + s_2s_1 & c_2s_3s_1 - s_2c_1 \\
-s_3 & c_3c_1 & c_3s_1 \\
s_2c_3 & s_2s_3c_1 - c_2s_1 & s_2s_3s_1 + c_2c_1
\end{bmatrix}
\]

\[
[4S^5] = \begin{bmatrix}
c_2c_3 & c_2s_3 & -s_2 \\
-s_3 & c_3 & 0 \\
s_2c_3 & s_2s_3 & c_2
\end{bmatrix} \tag{4.3}
\]

We associate for each element \( i \) the \( \vec{w}_{i+1} \) vector, where:

\( \vec{w}_{i+1} = O_i \vec{O}_{i+1} \).

\( O_i \) represents the origin of the \( R_i \) system and \( O_{i+1} \) the origin of the \( R_{i+1} \) system, associated with the element \( i+1 \).

\( M_1, M_2, M_3, \ldots, M_j \) are points of the kinematic elements for which it will be determined the speeds with respect to the global \( R_0 \) system.

The vector of position of \( M_j \) point, with respect to \( R_0 \) system, is given by Eq. (4.4).

\[
\vec{r}_{M_j}^{R_0} = \sum_{i=1}^{j} \{w_i^T \} [0S^{i-1}] \{i^0 \} + \{r_j \}^T [0S^j] \{i^0 \} \tag{4.4}
\]

To determine the angular speed it will be used equation (4.5).
\[ [^0\Omega^j] = [^0\dot{S}^j][^0S^j]^T \] (4.5)

where:

\[
[^0\Omega^j] = \begin{bmatrix}
0 & 0 & 0 \\
-\omega_3^j & 0 & 0 \\
\omega_2^j & -\omega_1^j & 0 \\
\end{bmatrix} \] (4.6)

We note:

\( (\omega_1^j, \omega_2^j, \omega_3^j) \) like \( \omega \) \( (\omega_{j_1}, \omega_{j_2}, \omega_{j_3}) = \{\omega_j\} \).

We calculate the angular speed of the element \( j \) with respect to the global system, with equation (4.7).

\[ \omega = \{\omega_j\}[^0\dot{S}^j][^0\dot{i}^0] \] (4.7)

Deriving the vector of position of one point \( M_j \) with respect to time we obtain the speed of the point with respect to \( Ro \) and deriving it two times we obtain its acceleration.

The program was run with the angular speed of the leader element = 83 rpm, similar to those of the \textit{Litobius forficatus} for the period of time 0 - 0.349 s.

The dimensions of the elements were: length of the cylinder =10 mm; radius of cylinder=4 mm; length of the element which corresponds to the leg of the millipede =12,071mm; angle of the cone =45\(^{\circ}\).

The results denote that the chosen geometry of the mechanism partially respects the kinematic of the millipede. The mechanism imitates the movement of millipedes in different successive positions in plane.

The number of actuators is 4 or 5 at a given moment.
G. Elimination of Contradictions Using the TRIZ method if the Probable Target Does Not Agree with the Wished Target

If the probable target does not agree with the wished target, the contradictions will be eliminated using the TRIZ method, becoming the new enhanced source. After this, the steps (E) and (F) are repeated.

Consciously or intuitively, everyone eliminates contradictions when they create something new in the domain of science or technique.

G1. The millipede

In this work there were many technical contradictions, such as:

- To keep the same main law of the locomotion of the animal’s body in plane, but with the simplest possible structure (in the contradiction matrix: adaptability/device complexity, 35/36);

- To keep great mobility, but with few actuators (in the contradiction matrix: adaptability/ease of operation, 35/33);

- To move in narrow spaces, with the same main law of movement of the animal, but without the great volume of the robot (in the contradiction matrix: adaptability/volume of an object that is moving, 35/7).

For the 35/36 technical contradictions, the matrix recommends: 15 (dynamics), 29 (hydraulic or pneumatic), 37 (thermal expansion), 28 (mechanics substitution).

For the 35/33 technical contradictions the matrix recommends: 15 (dynamics), 34 (discarding and recovering), 1 (segmentation) and 16 (partial or excessive action) as the inventive principles.

These two contradictions were unified.
In order to reproduce principal types of locomotion of the millipedes in plane, but with a simple device with minimum of motors, the inventive principles: discarding and recovering - 34, merging - 5, periodic action - 19, mechanics substitution - 28 and dynamics – 15, were used.

It was used a simplified scheme, obtained by: (a) discarding irrelevant degree of freedoms of some kinematic elements (inventive principle discarding and recovering - 34); and (b) assembling similar parts, different kinematic elements of the legs - to perform parallel operations: the same movement of the new legs (inventive principle merging -5).

Priority was given to the coordination of the movement with a minimum of number actuators.

Many ideas which were including the previous scheme were considered resulting in:

- the use of electromagnetic fields, fixing some points of legs (inventive principle 28) and
- a design process to find an optimal number of actuators by using one single rotational motor (inventive principle 15).

The periodic action (inventive principle 19) of the actuators was presented in [39], for different types of locomotion.

Fig. 4.27 depicts the new simpler structural model.

For this model it is interesting to remark that one single motor with alternating rotation (in joint B), and two actuating sliding or rotational joints on each of the ‘body’ elements (in joints: A and C1; M and C2; G1 and C3; G2 and N; G3 and O ...) are sufficient for the locomotion of this multi-legged mechanism, even if the set of four body-elements (Fig. 4.27) is repeated.
The robot presents certain geometrical restrictions established by analogy with the initial source, according to the morphological analysis: the elements 2, 4, 6, 8 ... are midlines in the passive chains.

There are variable kinematic chains during the locomotion which alternate from active to passive.

It was possible to establish the law for the command of the actuators on different curves in plane.

We choose a structural model with 5 pairs of legs (Fig. 4.28).

The structural model (Fig. 4.28) has 39 rigid kinematic elements, 45 rotation joints plus joints that are formed at the contact with the background (Fig. 4.28).

The segments of the body are substituted with the elements 1, 3, 5, 7, 9 and the ‘legs’ P1,..., P10 are situated at the end of these elements.
Figure 4.28

For this structural model some characteristics of one type of displacement of millipedes are used.

The projections of the legs on the horizontal plan are constant.
It is respected too, the law of setting of the legs on the background.

The structural model presents variable chains during locomotion.

For the kinematic calculus it was useful vectorial method and it was made a program in PASCAL language (ANNEXE).

It was determinated the optimal dimensions of the mechanism that realise displacement with the same kinematic parameters like real millipedes.

The principal goal was to obtain the same angular speeds for all equivalent elements of animal body segments, the same angular speeds for all equivalent elements of animal pair legs, with minimum of actuators.
For that, the dimensions of mechanism elements must respect the following conditions:
- for the value \( l_1 \) adopted, the length \( l_2 \) is determined with Eq. (4.8):

\[
l_2 = l_1 \sqrt{\frac{1}{2} (1 - \cos 45^\circ)}
\]  

(4.8)

- the point \( D \) coordinates are determined with the condition:
\(^\wedge\)ADC = 45^\circ \) (for the limited position).

The angular speed of the first pair of legs of the millipede was determined experimental with the help of the films (measurements and processing of the dates):
\( \varphi' = 500^\circ / s; \)
\( n = 83 \) rpm.

For the kinematic calculus of the mechanism it was utilised \( n = 83 \) rpm, \( l = 13.5 \) mm (like the real dimension of the sample).

With the obtained results it was realized the diagrams of angular positions, speeds and accelerations, with \( \varphi_1 \) from \( 45^\circ \) to \( 90^\circ \).

Compared with experimental measurements, the theoretical angular speed and acceleration are approximately equal.

\[
\omega_{\text{experimental}} \approx 450^\circ / s; \quad \omega_{\text{theoretical}} \approx 500^\circ / s; \\
\xi_{\text{experimental}} \approx 10000^\circ / s^2; \quad \xi_{\text{theoretical}} \approx 7000^\circ / s^2
\]
It was created a program in TURBO PASCAL planning to visualize the moving of the mechanism in curves, like in the Fig. 4.29.

The animation of the mechanism denotes a similitude with the real trajectory of the millipede during the movement.
The experimental model can be seen in Fig. 4.30. The dimensions of this model are: length = 0.4 m, width = 0.13 m, height = 0.08 m.

The type of the model is planar multi-legged robot. It weighs 1 kg and has a maximum velocity of 0.1 m/s.
To eliminate the contradiction: *adaptability/volume of an object that is moving*, 35/7, one of the inventive principle recommended in contradiction matrix, *dynamics* - 15 was used, in addition to *merging* - 5, *thermal contraction* - 37 and *spheroidality-curvature* - 14.

The robot shown in Fig. 4.30 can be adapted, becoming flexible, using shape memory actuators and flexure hinges.

By analogy shape memory actuators instead of rotational motors there are used, going from the idea that the muscles have three specific properties: elasticity, excitability and contractibility.

Thus, the inventive principle *thermal contraction* is applied, utilizing SMAs (shape memory alloys), which are metals that ‘remember’ their original forms. SMAs can change shape, stiffness, and other mechanical characteristics in response to temperature and stress.

Another inventive principle that was applied for the same contradiction was *spheroidality-curvature*.

For this reason flexure hinges were used instead of rotational joints.

The material of the mini-robot will allow it to become flexible (the principle: *dynamics*).

But, the law of movement on any curve in plane is the same, and thus the control for leading the ‘legs’ and for the main actuator is unchanged.

Results from an analysis with FEM (finite element method) using the COSMOS program for different situations [43], showed that the areas of flexure hinges were most stressed (Fig. 4.31).
Figure 4.31
H. The Internal or External Strain and the Comparison by Analogy with Possible Different Targets of Other Inventors

The history of technique proves that the maintenance of one idea in long-term memory, the intensive attention on it and the visual analogies has had an important role for creativity.

When Isaac Newton was asked about his method used in research he answered:
*I was thinking about a problem, I was keeping the subject of my research before my eyes, looking forward to the first light of my mind, until it has changed into a clear idea.*

It is said that the great inventor Michael Faraday was keeping in the pocket of his waistcoat a little magnet to remind him the most important preoccupation during his entire career.

If he was occasionally touching the magnet during the lectures, all the students were leaving the class in silence because they knew that the great teacher was thinking to the electromagnetism.

If an acceptable target is not found, and an internal or external strain influences the inventor, the selected scheme-source will be compared by analogy with possible different targets of other inventors, which are stored in the long-term memory or with other new possible targets that can be seen in the future.

We consider that this last complex process begins from the present to the past and it is furthered by cognitive historical analysis.

In this comparison, visual similarities with the primordial wished relationships are mapped.

If we obtain an acceptable model from the long-term memory, the process will be continued with transfer and evaluation, and can be repeated.
Some examples can be seen below. For *Lepidoptera*, some complex structural models of walking robots with rigid elements were realized (Fig. 4.16 and Fig. 4.17).

But, they were too complicated and had too many actuators leading to the conclusion that the targets were not acceptable, resulting in strain that influences the mind.

The scheme-source of *Lepidoptera* deduced from the complex model has permanently rested in the mind.

It is compared by analogy with different targets of other authors, stored in the long-term memory.

This process begins from the present to the past.

It is fixed on the last most impressive remembered image with visual similarities and the primordial wished relationships.

Our attention was fixed on the delightful snapshot presented by H. Steinhaus in 1939 without details (Fig. 4.32): two echidecomposable figures (the square and the equilateral triangle) and four little plates which compose the square or the triangle.

The inventor wrote:

*If we turn the lever up or down, with these four little plates we are able to compose a square or an equilateral triangle.*

Boltyansky defines two figures from the plane being echidecomposable if one of them can be decomposed in a finite number of parts that can be reorganized to form the second figure (Fig. 4.33).

Schoenberg presented in 1989 the construction of these four plates [35] (Figure 4.34).
A program in TURBO PASCAL was created, for kinematic calculus and simulation of the motion of a planar mechanism, that realizes a circular movement of the figures, alternating the square with the triangle (Fig. 4.35, Fig. 4.36).
Figure 4.36

Mapping and transfer from the enhanced source to the probable target continue the process: we agree with the new mechanism, but our preoccupation is to realize a walking mechanism; for that, the plate $a$ (Fig. 4.31) will be mobile.

We combine the experiments with thought experiments. We observed that this mechanism presented by Steinhaus can be used for the creation of a planar mechanism.

It reproduces a circular movement of the figures, alternating the square with the triangle (Fig. 4.37), or can reproduce the movement to right or to left (Fig. 4.38).

Figure 4.37
For a circular movement one or another marginal plate is fixed alternatively. It can use the three leading joints (each of them turned with $180^0$) or it can take action with only one motor on the plate $a$ (respectively $d$), actuating through cable the plates $b, c, d$ (respectively $a, b, c$). The cable pass over the circular plates fixed on each plate.

Fig. 4.39 depicts the experimental model of this mechanism actuating through one cable reeled on the two reels (Fig. 4.40).

If we attach ‘legs’ to each little plate, it must be taken into account that when the little plate is moving, the ‘legs’ must be raised from the substratum and when the little plate is fixed, the legs must be in contact with the substratum.
4.4 CONCLUSIONS

Bionics may be used successfully to create new walking robots.

The conclusions of the author after this study are synthesized in the answers to some questions:

- *What is the role of the image representation in the domain of bionics?*
  
  Visual analogy is the basis of scientific creation in bionics. This phase is so important because the scheme-source with selected relationships, especially mathematical and causal relationships, will be the new source-model.

  By discarding irrelevant relationships of the initial source and storing critical ones, a new scheme-source will be obtained.

- *Is it right to realize a minute morphological analysis and a minute analysis of locomotion, or is it better only to look at the general aspects of them?*

  It is right to obtain the relationships determined by morphology and main features of the locomotion; and finally, it is useful for the exercise (algorithms) of the mind.

- *What is the role of internal or external strain in creation in bionics?*

  It drives to eliminate the technical contradictions (intuitively or not) or to find in the long-term memory the results of other inventors, or to continue the process of analogy in the future.

- *What is the influence of time upon the last activated remembrance in the process of the analogy?*

  This process begins from the present to the past.

- *Why were some realizations from the history of science selected and utilized and not others?*
The influence of the intensity of the information stored in the long-term memory is very important in analogical process.

The last most impressive (positive or negative) remembered image, with visual similarities and the primordial wished relationships is fixed.

If internal or external strain forces to a continuity of the process, the next most impressive remembrance from the present to the past is fixed.

*If different steps of the process of scientific creation are followed or different creativity techniques studied and presented by others, will the result of the work in the same domain, for the same problem, be better, or the same?* Probably it will be better.
{5.1 PROGRAM FOR A KINEMATIC CALCULUS OF THE MECHANISM MMS4}

uses crt, dos, printer;
type vec = array[0..360] of real;
var xd, yd, xf, yf, xfp, yfp, xfpp, yfpp, xg, yg, l1, l2: real;
vf3, vfxc, vfyc, vf2dd, vf2, vf3d, vf2d, vf3dd, vcxd, vcyd, vcxdd, vcyydd, vf3r, vf2r, vfxcr, vfycr, vf3dr, vf2dr, vf3ddr, vf2ddr, vcxdrr, vcyyddr: vec;
aa: char; fi1, lab, lbc, lcrd, n1, xb, yb, fi2, fi3, fi4, fi5, a, b, c, xcr, ycr, xm, ym, pix, pix1, xcrpr, ycrpr, xcppr, ycppr: real;
var fi2p, fi3p, fi2pp, fi3pp, fi4p, fi5p, fi4pp, fi5pp, xcp, ycp, xcpp, ycpp: real;
var fi1p, xbp, ybp, xbpp, ybpp, t1, t2, xdp, ydp, xdpp, ydpp: real;
var i: integer;
procedure abel (fi1, lab, n1: real; 
var xb, yb, fi1p, xbp, ybp, xbpp, ybpp: real);
begin
fi1 := fi1 * pi / 180;
xb := lab * cos(fi1);
yb := lab * sin(fi1);
fi1p := pi * n1 / 30;
xbp := -fi1p * lab * sin(fi1);
ybp := fi1p * lab * cos(fi1);
xbpp := -sqr(fi1p) * lab * cos(fi1);
ybpp := -sqr(fi1p) * lab * sin(fi1);
end;
procedure labd10 (tt: integer; pix: real; xb, yb, xd, yd, xb, yb, xbpp, ybpp, xdp, ydp, xdpp, ydpp, lbc, lcrd: real; 
var xc, yc, fi2, fi3, a, b, c, fi2p, fi3p, fi2pp, fi3pp, xcp, ycp, xcpp, ycpp: real);
procedure labtrig (tt: integer; pix: real; a, b, c: real; var fin: real); 
var pp: real;
t1, t2: real;
begin
if c=a then begin t1:=(-a-c)/(2*b);t2:=t1;end
else
begin
t1:=(-2*b+sqrt(4*sqr(b)-4*(sqr(c)-sqr(a))))/(c-a)/2;
t2:=(-2*b-sqrt(4*sqr(b)-4*(sqr(c)-sqr(a))))/(c-a)/2;
end;
t1:=2*arctan(t1);
t2:=2*arctan(t2);
if tt=0 then
begin
clrscr;
writeln('t1=',t1*180/pi,'t2=',t2*180/pi);
writeln('Input value of the angle fi3 (\degree):');
readln(fin);
fin:=fin*pi/180;
end
else
begin
p:=abs(pix-t1);
pp:=abs(pix-t2);
if p<=pp then fin:=t1
else fin:=t2;
end;
end;
var w,z:real;
begin
a:=2*xd*lcd-2*xb*lcd;
b:=2*yd*lcd-2*yb*lcd;
c:=sqr(xd)+sqr(xb)-2*xd*xb+sqr(yd)+sqr(yb)-
 2*yd*yb+sqr(lcd)-sqr(lbc);
labtrig(tt,pix,a,b,c,fi3);
w:=(yd+lcd*sin(fi3)-yb)/lbc;
z:=(xd+lcd*cos(fi3)-xb)/lbc;
if (w>=0) and (z>0) then fi2:=arctan(abs(w/z))
else begin
  if(w>0) and(z<0)
  then fi2:=pi-arctan(abs(w/z))
  else begin
    if(w<0) and(z<0)
    then fi2:=pi+arctan(abs(w/z))
    else begin
      if(w<0) and (z>0)
      then fi2:=2*pi-arctan(abs(w/z))
      else begin
        if (w=1) and (z=0)
        then fi2:=pi/2
        else begin
          if (w=-1) and (z=0)
          then fi2:=3*pi/2
          end end
        end end
      end end
    end
    xc:=xb+lbc*cos(fi2);
    yc:=yb+lbc*sin(fi2);
    fi3p:=(ydp-ybp+(xdp-xbp)*cos(fi2)/sin(fi2))/
          (lcd*sin(fi3)*cos(fi2)/sin(fi2)-lcd*cos(fi3));
    fi2p:=(-xdp+xbp+fi3p*lcd*sin(fi3))/(lbc*sin(fi2));
    fi3pp:=(ybpp-lbc*sin(fi2)*sqr(fi2p)-ydpp+cos(fi2)*
            (xbpp-xdpp-lbc*cos(fi2)*sqr(fi2p)+lcd*cos(fi3)*sqr(fi3p))/
            sin(fi2)+lcd*sin(fi3)*sqr(fi3p))/(lbc*cos(fi3)-cos(fi2)*
            lcd*sin(fi3)/sin(fi2));
    fi2pp:=(xbpp-xdpp-lbc*cos(fi2)*sqr(fi2p)+lcd*cos(fi3)*
\[
sqr(fi3p) + lcd*\sin(fi3)*fi3pp) / (lbc*\sin(fi2));
\]
\[
xcp := xbp - lbc*\sin(fi2)*fi2p;
\]
\[
ycp := ybp + lbc*\cos(fi2)*fi2p;
\]
\[
xcpp := xbpp - lbc*\cos(fi2)*sqr(fi2p) - lbc*\sin(fi2)*fi2pp;
\]
\[
ycpp := ybpp - lbc*\sin(fi2)*sqr(fi2p) + lbc*\cos(fi2)*fi2pp;
\]
\end;
begin
clrscr;
writeln('The length of the driver element [mm] (real number)');
readln(l1);
writeln('The number of rpm of the driver element [rpm] (real number)');
readln(n1);
l2 := \sqrt{sqr(l1)/2 - sqr(l1)/2*cos(45*pi/180)};
xdp := 0; ydp := 0;
xd := l1*cos(45*pi/180);
yd := l1*sin(45*pi/180);
xg := 2*xd;
yg := 0;
for i := 45 to 90 do
begin
fi1 := i;
abel(fi1, l1/2, n1, xb, yb, fi1p, xbp, ybp, xbpp, ybpp);
labd10(i-45, pix, xb, yb, xd, yd, xbp, ybp, xbpp, ybpp, 0, 0, 0, 0, l2, l1/2, xc, yc, fi2, fi3, a, b, c, fi2p, fi3p, fi2pp, fi3pp, xcp, ycp, xcpp, ycpp);
pix := fi3;
vf3[i-44] := pix;
vf2[i-44] := fi2;
vfxc[i-44] := xc;
vfyc[i-44] := yc;
vf3d[i-44] := fi3p;
vf2d[i-44] := fi2p;
vf3dd[i-44] := fi3pp;
ANNEXE

vf2dd[i-44]:=fi2pp;
vcxd[i-44]:=xcp;
vcyd[i-44]:=ycp;
vcxdd[i-44]:=xcpp;
vcydd[i-44]:=ycpp;
end;
for i:=45 to 90 do
begin
xf:=xd+l1/2*cos(vf3[i-44]+45*pi/180);
yf:=yd+l1/2*sin(vf3[i-44]+45*pi/180);
xfp:=xdp-l1/2*vf3d[i-44]*sin(vf3[i-44]+45*pi/180);
yfp:=ydp+l1/2*vf3d[i-44]*cos(vf3[i-44]+45*pi/180);
xfpp:=xdpp-l1/2*(vf3dd[i-44]*sin(vf3[i-44]+45*pi/180)+
sqr(vf3d[i-44])*cos(vf3[i-44]+45*pi/180));
yfpp:=ydp+1/2*(vf3dd[i-44]*cos(vf3[i-44]+45*pi/180)-
sqr(vf3d[i-44])*sin(vf3[i-44]+45*pi/180));
labd10(i-45,pix1,xf,yf,xg,yg,xfp,yfp,xfpp,yfpp,0,0,0,0,
l2,l1/2,xcr,ycr,fi4,fi5,a,b,c,fi4p,fi5p,fi4pp,fi5pp,xcpr,
ycpr,xcppr,ycppr);
pix1:=fi5;
vf3r[i-44]:=pix1;
vf2r[i-44]:=fi4;
vfxcr[i-44]:=xcr;
vfycr[i-44]:=ycr;
vf3dr[i-44]:=fi5p;
vf2dr[i-44]:=fi4p;
vf3ddr[i-44]:=fi5pp;
vf2ddr[i-44]:=fi4pp;
vcxdr[i-44]:=xcpr;
vcydr[i-44]:=ycpr;
vcxddr[i-44]:=xcppr;
vcyddr[i-44]:=ycppr;
end;
for i:=45 to 90 do 
begin 
writeln('      fi1=',i,'[°]', '  fi3=',vf3[i-44]*180/pi:10:2, '[°]', '  fi2=',vf2[i-44]*180/pi:10:2,'[°]');
end; readln;
for i:=45 to 90 do 
begin 
writeln('      fi1=',i,'[°]', '  om3=',vf3d[i-44]*180/pi:10:2, '[°/s]', '  om2=',vf2d[i-44]*180/pi:10:2,'[°/s]');
end; readln;
for i:=45 to 90 do 
begin 
writeln('      fi1=',i,'[°]', '  eps3=',vf3dd[i-44]*180/pi:10:2, '[°/s^2]', '  eps2=',vf2dd[i-44]*180/pi:10:2,'[°/s^2]');
end; readln;
for i:=45 to 90 do 
begin 
writeln('      fi1=',i,'[°]', '       xc=',vfxc[i-44]:10:2, '[mm]', '     yc=',vfyc[i-44]:10:2,'[mm]');
end;
readln;
for i:=45 to 90 do 
begin 
writeln('      fi1=',i,'[°]', '       xcp=',vcxd[i-44]:10:2, '[mm/s]', '       ycp=',vcyd[i-44]:10:2,'[mm/s]');
end; readln;
for i:=45 to 90 do 
begin 
writeln('      fi1=',i,'[°]', '       xcpp=',vcxdd[i-44]:10:2, '[mm/s^2]', '       ycpp=',vcydd[i-44]:10:2,'[mm/s^2]');
end; readln;
for i:=45 to 90 do 
begin 

ANNEXE

writeln('   fi1=',i,'[°]', '   fi5=',vf3r[i-44]*180/pi:10:2,'[°]');
end; readln;
for i:=45 to 90 do
begin
writeln('   fi1=',i,'[°]', '   fi4=',vf2r[i-44]*180/pi:10:2,'[°]');
end; readln;
for i:=45 to 90 do
begin
writeln('   fi1=',i,'[°]', '   om5=',vf3dr[i-44]*180/pi:10:2,'[°/s]','   om4=',vf2dr[i-44]*180/pi:10:2,'[°/s]');
end; readln;
for i:=45 to 90 do
begin
writeln('   fi1=',i,'[°]', '   eps5=',vf3ddr[i-44]*180/pi:10:2,'[°/s^2]','   eps4=',vf2ddr[i-44]*180/pi:10:2,'[°/s^2]');
end; readln;
for i:=45 to 90 do
begin
writeln('   fi1=',i,'[°]', '   xm=',vfxcr[i-44]:10:2,'[mm]','   ym=',vfycr[i-44]:10:2,'[mm]');
end; readln;
for i:=45 to 90 do
begin
writeln('   fi1=',i,'[°]', '   xmp=',vcxdr[i-44]:10:2,'[mm/s]','   ymp=',vcydr[i-44]:10:2,'[mm/s]');
end; readln;
for i:=45 to 90 do
begin
writeln('   fi1=',i,'[°]', '   xmpp=',vcxddr[i-44]:10:2,'[mm/s^2]','   ympp=',vcyddr[i-44]:10:2,'[mm/s^2]');
end;
repeat aa:=readkey until aa=#27;
end.
ANNEXE

{5.2 PROGRAM FOR THE SIMULATION OF THE MOVEMENT OF A MECHANISM INSPIRED BY THE PLANAR MOVEMENT OF MILLIPEDES}

uses crt, dos, graph;
const detect = 0;
type vec = array[0..360] of real;
veec = array[0..360] of integer;
var k, k1, l1, l2, ns, dir, xo, yo, sc, xd, yd, xd1, yd1, xd2, yd2, xg1,
yg1, xff, yff, xd22, yd22, xd222, yd222, xfd2, yfd2: integer;
alf, pif, ppif, xe1, ye1, xe, ye, xf, yf, xg, yg, xp, yp: real;
vf3, vf2, vf4, vf5, vf31, vf21: vec;
vpx, vpy: veeec;
aa: char; fi1, lab, lbc, lcd, n1, la, lb, lc, xb, yb, fi2, fi3, fi4, fi5,
a, b, c, a1, a2, a3, xc, yc, xc1, yc1, xm, ym, pix, pix1, ppix, xb1, yb1,
fi21, fi31: real;
var fi2p, fi3p, fi2pp, fi3pp, fi4p, fi5p, fi4pp, fi5pp, xmp, ymp, xmpp,
ympp, xcp, ycp, xcpp, ycpp, xg1p, yg1p, xg1pp, yg1pp, xn, yn: real;
var fi1p, xbp, ybp, xbpp, ybpp, t1, t2, t3, t4, xdp, ydp, xdp1, ydp: real;
var gd, gm, corx, cory, cor1x, cor1y, i, j, coo, co, gg, ggg: integer;
{$I abel.pas}; {$I labd10.pas};
{main program}
begin
initgraph(gd, gm, 'c:\bp\bgi');
if graphresult <> 0 then
  writeln(grapherrormsg(graphresult));
cleardevice;
setbkcolor(white);
settextstyle(3, horizdir, 2);
setcolor(magenta);
outtextxy(1, 1, 'University of Craiova');
outtextxy(1, 1 + textheight('F'), 'Faculty of Mechanics');
settextjustify(center, center);
setcolor(red);
Program for the simulation of the planar movement of a mechanism with one motor, inspired by the movement of millipedes;

Dr. Eng. Simona-Mariana Cretu;

delay(10000);
cleardevice;
l1:=135;
l2:=trunc(sqrt(sqr(l1)/2-sqr(l1)/2*cos(45*pi/180)));
fi1:=0.;
yo:=trunc(2*getmaxy/5);
xo:=trunc(getmaxx/2);
setgraphmode(gm);
for I:=1 to 360 do
begin
    setcolor(yellow);
    line(xo,yo,xo+trunc(9*l1*cos(I*3.141592/180)),yo-trunc(9*l1*sin(I*3.141592/180)));
    delay(5);
end;
for i:=45 to 90 do
begin
    fi1:=i;
    abel(fi1,l1/2,10,xb,yb,fi1p,xbp,ybp,xbpp,ybpp);
    xdp:=0;ydp:=0;
    xg1p:=0;yg1p:=0;
    xd:=xo+trunc(l1*cos(45*3.141592/180));
yd:=yo-trunc(l1*sin(45*3.141592/180));
ANNEXE

\[ x_{d1} := x_0 - \text{trunc}(l_1 \cos(45 \times 3.141592/180)); \]
\[ y_{d1} := y_d; \]
\[ x_{b} := x_0 + x_b; \quad y_{b} := y_0 - y_b; \]
\[ x_{g1} := x_d + \text{trunc}(l_1 \cos(45 \times 3.141592/180)); \]
\[ y_{g1} := y_0; \]
\[ \text{labd10}(i, \text{pix}, x_b, y_b, x_d, y_d, l_2, l_1/2, x_c, y_c, f_i2, f_i3, a, b, c, f_i2p, f_i3p, f_i2pp, f_i3pp, x_{cp}, y_{cp}, x_{cpp}, y_{cpp}, x_d, y_d, x_{dpp}, y_{dpp}); \]
\[ \text{pix} := f_i3; \quad \text{vf3}[i] := \text{pix}; \]
\[ x_g := x_d + l_1 \cos(\text{vf3}[i] - 45 \times \pi/180); \]
\[ y_g := y_d + l_1 \sin(\text{vf3}[i] - 45 \times \pi/180); \]
\[ x_f := (x_d + x_g)/2; \quad y_f := (y_d + y_g)/2; \]
end;

setgraphmode(gm);
cleardevice;
setviewport(1,1,\text{getmaxx},10+2\times\text{textheight}(P'),false);
setbkcolor(white); setcolor(blue);
settextstyle(3,horizdir,3);
settextjustify(centeredtext,toptext);
outtextxy(\text{getmaxx} div 2,5,'Straight going ');
outtextxy(\text{getmaxx} div 2,5+\text{textheight}(P'),
'of the mechanism inspired by the movement of millipedes');
setviewport(1,5+2\times\text{textheight}(P')+2,\text{getmaxx},\text{getmaxy},false);

-----------------------------------------------------------------------------------------------
cleardevice;
setviewport(1,1,\text{getmaxx},10+2\times\text{textheight}(P'),false);
setcolor(white);
settextstyle(3,horizdir,3);
settextjustify(centeredtext,toptext);
outtextxy(\text{getmaxx} div 2,5,'movement in a curve ');
outtextxy(\text{getmaxx} div 2,5+\text{textheight}(P'),
'of the mechanism inspired by the movement of millipedes');
setviewport(1,5+2\times\text{textheight}(P')+2,\text{getmaxx},\text{getmaxy},false);
for k1:=1 to 2 do
begin
j:=1;
repeat
for i:=45 to 90 do
begin

clearviewport;
pif:=vf3[I];
ex:=xd+l1*cos(pif);
ye:=yd+l1*sin(pif);
exg:=xd+l1*cos(pif-45*pi/180);
yg:=yd+l1*sin(pif-45*pi/180);
xf:=(xd+xd)/2;
yf:=(yd+yd)/2;
setcolor(yellow);
setlinestyle(0,1,3);
setcolor(yellow);
xff:=xo+trunc(l1*cos(i*3.141592/180));
yff:=yo-trunc(l1*sin(i*3.141592/180));
if (j=1) or (j=2) or (j=3) or (j=4) or (j=5) then
begin
line(xo,yo,xff,yff);
end;
if (j=1) or (j=2) or (j=3) or (j=4) then
begin
line(xo+trunc(l1/2*cos(i*3.141592/180)),yo-trunc(l1/2*
    sin(i*3.141592/180)),trunc((xe+xd)/2),trunc((ye+yd)/2));
line(trunc(xd),trunc(yd),trunc(xe),trunc(ye));
xm:=xg1+trunc(l1/2*cos(pif));
ym:=yg1-trunc(l1/2*sin(pif));
xn:=xg1+trunc(l1/2*cos(pif-45*3.141592/180));
yn:=yg1-trunc(l1/2*sin(pif-45*3.141592/180));
xp:=xg1+trunc(l1*cos(pif-45*3.141592/180));
yp:=yg1-trunc(l1*sin(pif-45*3.141592/180));

end;
end;
if (j=1) or (j=2) then
begin
line(xg1,yg1,xg1+trunc(l1*cos(pif)),yg1-trunc(l1*sin(pif)));
line(trunc(xf),trunc(yf),trunc(xm),trunc(ym));
end;
if j=1
then
begin
line(trunc(xn),trunc(yn),trunc(xm),trunc(ym));
line(xg1,yg1,trunc(xp),trunc(yp));
end; delay(20);
alf:=120;
if (j=1) or (j=2) or (j=3) then
begin
line(trunc((xd+xe)/2),trunc((yd+ye)/2),trunc(xf),trunc(yf));
line(trunc(xd),trunc(yd),trunc(xg),trunc(yg));
end;
if (j=4) or (j=5) or (j=6) or (j=7) or (j=8)
then
begin
xd22:=xo+trunc(l1*cos((135+i)*3.141592/180));
yd22:=yo-trunc(l1*sin((135+i)*3.141592/180));
line(xo,yo,xd22,yd22);
end;
if (j=4) or (j=5) or (j=6) or (j=7)
then
line(trunc((xo+xd22)/2),trunc((yo+yd22)/2),xo+
trunc(l1/2*cos((i+90)*3.141592/180)),yo-trunc(l1/2*
sin((i+90)*3.141592/180)));
if (j=2) or (j=3) or (j=4) or (j=5) or (j=6)
then
\begin{verbatim}
line(xo,yo,xo+trunc(l1*cos((i+45)*3.141592/180)),yo-
trunc(l1*sin((i+45)*3.141592/180))); if (j=2) or (j=3) or (j=4) or (j=5)
then line(xo+trunc(l1/2*cos((i+45)*3.141592/180)),yo-trunc(l1/2*
sin((i+45)*3.141592/180)),xo+trunc(l1/2*cos(i*3.141592/180)
),yo-trunc(l1/2*sin(i*3.141592/180))); xd222:=xo+trunc(l1*cos((180+i)*3.141592/180));
yd222:=yo-trunc(l1*sin((180+i)*3.141592/180)); if (j=5) then
begin line(xo,yo,xd222,yd222);
line(trunc((xd222+xo)/2),trunc((yd222+yo)/2),trunc((xd22+xo)
/2),trunc((yd22+yo)/2)); end;
xd2:=xo+trunc(l1*cos((90+i)*3.141592/180));
yd2:=yo-trunc(l1*sin((90+i)*3.141592/180)); if (j=3) or (j=4) or (j=5) or (j=6)
then begin line(trunc((xo+xd2)/2),trunc((yo+yd2)/2),
xo+trunc(l1/2*cos((i+45)*3.141592/180)),yo-trunc(l1/2*
sin((i+45)*3.141592/180))); delay(20); end;
xfd2:=xo;
yfd2:=yo+l1; if (j=3) or (j=4) or (j=5) or (j=6) or (j=7) then
line(xo,yo,xfd2,yfd2);
xel1:=xo+l1*cos(135*pi/180+pif);
yel1:=yo-l1*sin(135*pi/180+pif);
if (j=6) or (j=7) or (j=8) or (j=9) then
begin
\end{verbatim}
xb1:=xfd2+trunc((l1*cos((135-i)*pi/180))/2);
yb1:=yfd2-trunc((l1*sin((135-i)*pi/180))/2);
line(xo,yo,trunc(xe1),trunc(ye1));
line(trunc(xb1),trunc(yb1),trunc((xo+xe1)/2),
trunc((yo+ye1)/2)); end;
if (j=6) or (j=7) or (j=8) or (j=9) or (j=10) then
  line(xfd2,yfd2,xfd2+trunc(l1*cos((135-i)*pi/180)),
yfd2-trunc(l1*sin((135-i)*pi/180)));
end;
if (j=6) or (j=7) or (j=8) then
  line(trunc((xd22+xo)/2),trunc((yd22+yo)/2),
  trunc((xo+xe1)/2),trunc((yo+ye1)/2));
end;
if (j=7) or (j=8) or (j=9) or (j=10) or (j=11) then
  line(xfd2,yfd2,xfd2+trunc(l1*cos((90-i)*pi/180)),
yfd2-trunc(l1*sin((90-i)*pi/180)));
end;
if (j=7) or (j=8) or (j=9) or (j=10) then
  line(xfd2+trunc((l1*cos((90-i)*pi/180))/2),
yfd2-trunc((l1*sin((90-i)*pi/180))/2),
  xfd2+trunc((l1*cos((135-i)*pi/180))/2),yfd2-
  trunc((l1*sin((135-i)*pi/180))/2));
end;
if (j=8) or (j=9) or (j=10) or (j=11) then
  begin
    line(xfd2+l1,yfd2,xfd2+l1+trunc(l1*cos((135+i)*pi/180)),
yfd2-trunc(l1*sin((135+i)*pi/180)));
    line(xfd2+l1+trunc((l1*cos((135+i)*pi/180))/2),yfd2-
    trunc((l1*sin((135+i)*pi/180))/2),
    xfd2+trunc((l1*cos((135-i)*pi/180))/2),yfd2-trunc((l1*
    sin((135-i)*pi/180))/2));
  end;
if (j=9) or (j=10) or (j=11) then
  begin
    line(xfd2+l1,yfd2,xfd2+l1+trunc(l1*cos((180+i)*pi/180)),
yfd2-trunc(l1*sin((180+i)*pi/180)));
    line(xfd2+l1+trunc((l1*cos((180+i)*pi/180))/2),yfd2-
    trunc((l1*sin((180+i)*pi/180))/2),
    xfd2+trunc((l1*cos((90-i)*pi/180))/2),yfd2-trunc((l1*
    sin((90-i)*pi/180))/2));
  end;
trunc((l1*sin((180+i)*pi/180))/2),
xfd2+l1+trunc((l1*cos((135+i)*pi/180))/2),yfd2-trunc((l1*sin((135+i)*pi/180))/2));
end;
if (j=10) or (j=11) then begin
line(xfd2+l1,yfd2+l1,xfd2+l1+trunc(l1*cos((135-i)*pi/180)),yfd2+l1-trunc(l1*sin((135-i)*pi/180)));
line(xfd2+l1+trunc((l1*cos((135-i)*pi/180))/2),yfd2+l1-trunc((l1*sin((135-i)*pi/180))/2),
xfd2+l1+trunc((l1*cos((180+i)*pi/180))/2),yfd2-trunc((l1*sin((180+i)*pi/180))/2));
end;
if j=11 then begin
line(xfd2+l1,yfd2+l1,xfd2+l1+trunc(l1*cos((90-i)*pi/180)),yfd2+l1-trunc(l1*sin((90-i)*pi/180)));
line(xfd2+l1+trunc((l1*cos((90-i)*pi/180))/2),yfd2+l1-trunc((l1*sin((90-i)*pi/180))/2),
xfd2+l1+trunc(l1/2*cos((135-i)*pi/180)),yfd2+l1-trunc(l1/2*sin((135-i)*pi/180)));
delay(100);
end;
j:=j+1;
until j=12;
end;
closegraph;
end.
{5.3 PROGRAM FOR THE SIMULATION OF THE MOVEMENT OF A MECHANISM INSPIRED BY THE MOVEMENT OF CATERPILLARS}

uses crt, dos, graph;
const detect = 0;
type mm = array[1..7] of string[50];
nn1 = array[1..7] of integer;
vec = array[0..360] of real;
veec = array[0..360] of integer;
const m: mm =
  ('length of one segment        ',
   'length of connection elements ',
   'number of the segments       ',
   'direction of the movement    ',
   'scale of the drawing         ',
   'x of the first point          ',
   'y of the first point          ');
var gbo, fd1, fc1, fa2, clb, fb, ba2, ga2, cbo: real;
var
  xf1, yf1, xbo, ybo, xd3, yd3, xa2, ya2, xb1, yb1, xf, yf, xd1, yd1, xc1,
  xb2, yb2, xbo1, ybo1, yc1, xg1, yg1: integer;
var k, k1, l1, l2, ns, dir, xo, yo, sc, xd, yd, xd2, yd2, xff, yff,
  xd22, yd22, xd222, yd222: integer;
alf, pif, ppif, xe, ye, xg, yg, xp, yp: real;
fl: file of integer;
nr: nn1; vf3, vf2, vf4, vf5: vec;
vp, vpy: veec;
aa: char; fi1, lab, lbc, lcd, n1, la, lb, lc, fi2, fi3, fi4, fi5,
a, b, c, a1, a2, a3, xc, yc, xm, ym, pix, ppix: real;
var fi2p, fi3p, fi2pp, fi3pp, fi4p, fi5p, fi4pp, fi5pp, xmp, ymp, xmpp,
  ympp, xcp, ycp, xcpp, ycpp, xg1p, yg1p, xg1pp, yg1pp, xn, yn: real;
var fi1p, xb, yb, xbp, ybp, xbpp, ybpp, t1, t2, t3, t4, xdp, ydp,
  xdpp, ydpp: real;
var gd, gm, corx, cory, cor1x, cor1y, i, j, coo, co, gg, ggg: integer;
{$I abelpas} ;
{$I labd10.pas}
begin
initgraph(gd, gm, 'c:\bp\bgi');
if graphresult <> 0 then
writeln(grapherrormsg(graphresult));
cleardevice;
setbkcolor(white);
settextstyle(3, horizdir, 1);
setcolor(magenta);
outtextxy(1, 1, 'University of Craiova');
outtextxy(1, 1 + textheight('F'), 'Faculty of Mechanics');
settextjustify(centertext, centertext);
setcolor(red);
settextstyle(3, horizdir, 3);
outtextxy(getmaxx div 2, getmaxy div 2 - textheight('P'),
'Program for the simulation of planar movement ');
outtextxy(getmaxx div 2, getmaxy div 2,
'of a mechanism with one motor ');
outtextxy(getmaxx div 2, getmaxy div 2 + textheight('P'),
'inspired by the movement of caterpillars');
setcolor(blue);
settextstyle(3, horizdir, 2);
outtextxy(getmaxx div 2, getmaxy div 2 + 3 * textheight('A'),
'Dr. Eng. Simona-Mariana Cretu');
delay(4);
cleardevice;
restorecrtmode;
textmode(259);
window(5, 5, 74, 74);
textbackground(lightgray);
crlscr;
textcolor(red);
assign(f1,'patrat.dat');
{$I-$}
reset(f1);
{$I+$}
if ioresult <> grok then begin
rewrite(f1);
for i:=1 to 7 do begin write(m[i]);
read (nr[i]);
write(f1,nr[i]);
end;
close (f1);
repeat delay(5) until readkey=#13;
end
else begin
for i:=1 to 7 do begin
read(f1,nr[i]);
writeln(m[i],nr[i]:10);
end;
close(f1);
repeat delay(5) until readkey=#13;
end;
l1:=nr[1];
l2:=trunc(sqrt(sqr(l1)/2-sqr(l1)/2*cos(45*3.141592/180)));
ns:=nr[3];
dir:=nr[4];
sc:=nr[5];
fi1:=0.;
yo:=trunc(getmaxy/4);
xo:=trunc(getmaxx/2);
setgraphmode(gm);
setcolor(yellow);
for i:=45 to 90 do
begin
fi1:=i;
abel(fi1,l1/2,10,xb,yb,fi1p,xbp,ybp,xbpp,ybpp);
xdp:=0;ydp:=0;
xglp:=0;yglp:=0;
xd:=xo+trunc(l1*cos(45*3.141592/180));
yd:=yo-trunc(l1*sin(45*3.141592/180));
xd1:=xo-trunc(l1*cos(45*3.141592/180));
yd1:=yd;
xb:=xo+xb;
yb:=yo-yb;
xg1:=xd+trunc(l1*cos(45*3.1411592/180));
yg1:=yo;
labd10(i,pix,xb,yb,xd,yd,l2,l1/2,xc,yc,fi2,fi3,a,b,c,fi2p,fi3p,fi2pp,fi3pp,xcp,ycp,xcpp,ycpp,xdp,ydp,xdpp,ydpp);
pix:=fi3;
vf3[i]:=pix;
vf2[i]:=fi2;
xg:=xd+l1*cos(vf3[i]-45*pi/180);
yg:=yd+l1*sin(vf3[i]-45*pi/180);
end;
setgraphmode(gm);
cleardevice;
setviewport(1,1,getmaxx,10+2*textheight('P'),false);
setbkcolor(white);
setcolor(blue);
settextstyle(3,horizdir,3);
settextjustify(centertext,toptext);
outtextxy(getmaxx div 2,5,'Two echidecomposable figures made from');
outtextxy(getmaxx div 2,5+textheight('P'),'four little plates');
setviewport(1,5+2*textheight('P')+2,getmaxx,getmaxy,false);
for i:=0 to 540 do begin 
clearviewport;
fd1:=l1/2;
fcl:=sqrt(3)*l1/2;fa2:=sqrt(7)*l1/2;
c1b:=sqrt(3/7)*l1;fb:=1.5/sqrt(7)*l1;
ba2:=(sqrt(7)/2-1.5/sqrt(7))*l1;
ga2:=sqrt(3)*l1/2;
gbo:=c1b;xd1:=xo;yd1:=yo;f1:=240;
xf:=xd1+trunc(l1/2*cos(f1*pi/180));
yf:=yd1-trunc(l1/2*sin(f1*pi/180));
xc1:=xd1+trunc(l1*cos((f1+60)*pi/180));
yc1:=yd1-trunc(l1*sin((f1+60)*pi/180));
fi2:=arctan(sqrt(3)/2);
xb1:=xc1+trunc(c1b*cos((f1-90)*pi/180+fi2));
yb1:=yc1-trunc(c1b*sin((f1-90)*pi/180+fi2));
line(xd1,yd1,xf,yf);
line(xd1,yd1,xc1,yc1);
line(xb1,yb1,xc1,yc1);
line(xf,yf,xb1,yb1);
setcolor(red);
if (i>=0) and (i<=360) then begin 
xd2:=xc1+trunc(l1*cos((f1+60)*pi/180));
yd2:=yc1-trunc(l1*sin((f1+60)*pi/180));
xa2:=xd2+trunc(l1*cos((f1-60)*pi/180));
ya2:=yd2-trunc(l1*sin((f1-60)*pi/180));
xb2:=xc1+trunc(c1b*cos((f1-90)*pi/180+fi2));
yb2:=yc1-trunc(c1b*sin((f1-90)*pi/180+fi2));
end else begin 
xd2:=xc1+trunc(l1*cos((f1+i-300)*pi/180));
ANNEXE

\[
y_{d2} := y_{c1} - \text{trunc}(l1 \cdot \sin((fi1 + i - 300) \cdot \pi/180));
\]
\[
x_{a2} := ad2 + \text{trunc}(l1 \cdot \cos((fi1 + i - 420) \cdot \pi/180));
\]
\[
y_{a2} := y_{d2} - \text{trunc}(l1 \cdot \sin((fi1 + i - 420) \cdot \pi/180));
\]
\[
x_{b2} := xc1 + \text{trunc}(c1b \cdot \cos((fi1 + i - 450) \cdot \pi/180 + fi2));
\]
\[
y_{b2} := y_{c1} - \text{trunc}(c1b \cdot \sin((fi1 + i - 450) \cdot \pi/180 + fi2));
\]
\]
\end{verbatim}

```plaintext
end;
line(xd2,yd2,xc1,yc1);
line(xd2,yd2,xa2,ya2);
line(xa2,ya2,xb2,yb2);
line(xb2,yb2,xc1,yc1);
fi3 := 180;
if (i <= 180) and (i >= 0) then
begin
xd3 := xa2 + \text{trunc}(l1 \cdot \cos(fi3 \cdot \pi/180));
yd3 := ya2 - \text{trunc}(l1 \cdot \sin(fi3 \cdot \pi/180));
xg1 := xa2 + \text{trunc}(ga2 \cdot \cos((fi3 - 30) \cdot \pi/180));
yg1 := ya2 - \text{trunc}(ga2 \cdot \sin((fi3 - 30) \cdot \pi/180));
xbo := xg1 + \text{trunc}(c1b \cdot \cos(fi2 - 30 \cdot \pi/180));
ybo := yg1 - \text{trunc}(c1b \cdot \sin(fi2 - 30 \cdot \pi/180));
end
else
begin
xd3 := xa2 + \text{trunc}(l1 \cdot \cos((fi3 + i - 180) \cdot \pi/180));
yd3 := ya2 - \text{trunc}(l1 \cdot \sin((fi3 + i - 180) \cdot \pi/180));
xg1 := xa2 + \text{trunc}(ga2 \cdot \cos((fi3 + i - 210) \cdot \pi/180));
yg1 := ya2 - \text{trunc}(ga2 \cdot \sin((fi3 + i - 210) \cdot \pi/180));
xbo := xg1 + \text{trunc}(c1b \cdot \cos(fi2 + (i - 210) \cdot \pi/180));
ybo := yg1 - \text{trunc}(c1b \cdot \sin(fi2 + (i - 210) \cdot \pi/180));
end;
setcolor(magenta);
line(xa2,ya2,xd3,yd3);
line(xd3,yd3,xg1,yg1);
line(xg1,yg1,xbo,ybo);
```
line(xbo,ybo,xa2,ya2);
setcolor(green);
xf1:=xg1+trunc(l1*cos((60+i)*pi/180));
yf1:=yg1-trunc(l1*sin((60+i)*pi/180));
xbo1:=xg1+trunc(c1b*cos(fi2+(i-30)*pi/180));
ybo1:=yg1-trunc(c1b*sin(fi2+(i-30)*pi/180));
line(xg1,yg1,xf1,yf1);
line(xf1,yf1,xbo1,ybo1);
line(xg1,yg1,xbo1,ybo1);
repeat delay(5)
until keypressed;
end;
closegraph;
end.
uses graph,crt;
const detect=0;
type mm=array[1..40] of string[70];
t=[1..1,1..3] of real;
t1=[1..3,1..3] of real;
s=[1..15,1..1] of real;
ss1=[1..15,1..3] of real;
sss=[1..1,1..15] of real;
n1=[1..40] of real;
const m:mm=(
'El. 1 rotates around the axis: 1,2,3;0-none       ',
'El. 2 rotates around the axis: 1,2,3;0-none       ',
'El. 3 rotates around the axis: 1,2,3;0-none       ',
'El. 4 rotates around the axis: 1,2,3;0-none       ',
'El. 5 rotates around the axis: 1,2,3;0-none       ',
'Angular speed for el. 1 around the mentioned axis        ',
'Angular speed for el. 2 around the mentioned axis        ',
'Angular speed for el. 3 around the mentioned axis        ',
'Angular speed for el. 4 around the mentioned axis        ',
'Angular speed for el. 5 around the mentioned axis        ',
'The constant angle of rotation of the system 1 around first axis (\theta)',
'The constant angle of rotation of the system 2 around first axis (\theta)',
'The constant angle of rotation of the system 3 around first axis (\theta)',
'The constant angle of rotation of the system 4 around first axis (\theta)',
'The constant angle of rotation of the system 5 around first axis (\theta)',
'The constant angle of rotation of the system 1 around the
axis 2(0)',
'The constant angle of rotation of the system 2 around the axis 2(0)',
'The constant angle of rotation of the system 3 around the axis 2(0)',
'The constant angle of rotation of the system 4 around the axis 2(0)',
'The constant angle of rotation of the system 5 around the axis 2(0)',
'The constant angle of rotation of the system 1 around the axis 3(0)',
'The constant angle of rotation of the system 2 around the axis 3(0)',
'The constant angle of rotation of the system 3 around the axis 3(0)',
'The constant angle of rotation of the system 4 around the axis 3(0)',
'The constant angle of rotation of the system 5 around the axis 3(0)',
'The time for calculus',
'X1 – of the origin of system 2 in the coordinate system 1',
'Y1 - of the origin of system 2 in the coordinate system 1',
'X2 - of the origin of system 3 the to coordinate system 2',
'Y2 - of the origin of system 3 the to coordinate system 2',
'X of the centre of mass C1 in its coordinate system',
'Y of the centre of mass C1 in its coordinate system',
'X of the centre of mass C2 in its coordinate system',
'Y of the centre of mass C2 in its coordinate system',
'X of the centre of mass C3 in its coordinate system',
'Y of the centre of mass C3 in its coordinate system',
'X of the centre of mass C4 in its coordinate system',
'Y of the centre of mass C4 in its coordinate system',
'X of the centre of mass C5 in its coordinate system',
'Y of the centre of mass C5 in its coordinate system',

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'Y of the centre of mass C5 in its coordinate system');

var n,m,p:integer; tim,fi1,fi2,fi3,fi1p,fi2p,fi3p,cc:real;
k,i,J,jj,gd,gl,r1,r2:integer;
f1:file of real;
s1,s01,s12,s23,s34,s45,s02,s03,s04,s05,s01t,s02t,s03t,s04t,
s05t:t1;
s1p,s01p,s12p,s23p,s34p,s45p,s02p,s03p,s04p,s05p,s02p1,
s02p2,s03p1,s03p2,s04p1,s04p2,ad1,ad2,ad3,ad4,ad5,ad6,
rc1,rc2,rc3,rc4,rc5:t1;
om1,om2,om3,om4,om5:t1;v1,v2,v3,v4,v5,v6:ss1;
omp:s; qrd,ompt:sss; vit3:t;
o1,o2,o3,o4,o5:t1;vit1,vit2,vit4,vit5,vit6:t;
ar1,ar2,ar3,ar4,AR5,aw2,aw3,aw4,aw5,om01,om02,om03,
om04,om05,mp1,mp2,mp3,mp4,mp6,mp8,mp10,w2,w3,w4,
w5,rr1,rr2,rr3,rr4,rr5:t1;
qgen:array[1..15] of real;q:array[1..5] of real;
nr:n1;a:char;str1,str3,str4,str5,str2,str6:string[70];
ume_fis:string;

{$i ini_fis.pas} {$i move2.pas}
{$i tas_trei.pas} {$i tab1.pas}
{$i tab2.pas} {$i mat1.pas}
{$i mat.pas} {$i ad.pas}

begin
initgraph(gd,gm,'c:\bp\bgi');
if graphresult <> grok then
begin writeln(grapherrormsg(graphresult));halt(1);
end;
cleardevice;
setcolor(1);setbkcolor(white);
settextstyle(3,0,4);settextjustify(centertext,centertext);
outtextxy(getmaxx div 2,getmaxy div 2-textheight('P'),
'Program for a kinematic calculus');
outtextxy(getmaxx div 2, getmaxy div 2 + textheight('P'), 'of a robot');
readln; setbkcolor(3); setcolor(4);
for i:=1 to 5 do begin delay(200);
  fillellipse(getmaxx div 2, getmaxy div 2, 80*i, 80*i);
end;
restorecrtmode; textmode(259);
window(1,1,79,79);
textbackground(lightgray); clrscr; textcolor(red);
assign(f1, 'a1.dat');
ini_fis('a1.dat', 40, 40);
tas_trei(a, 40, 40);
tim:=nr[26];
for i:=1 to 5 do q[i]:=nr[i+5]*tim;
jj:=0;
for i:=1 to 5 do
begin
  if (nr[i]=3) then
  begin
    qgen[3+jj]:=q[i]; qgen[2+jj]:=0; qgen[1+jj]:=0;
    fi1:=(nr[10+i])*pi/180;
    fi2:=(nr[15+i])*pi/180;
    fi3:=(q[i]+nr[i+20])*pi/180;
    fi1p:=0; fi2p:=0; fi3p:=nr[5+i];
  end
  else
  begin
    if (nr[i]=2) then
    begin
      qgen[2+jj]:=nr[5+i]*tim; qgen[1+jj]:=0; qgen[3+jj]:=0;
      fi1:=nr[10+i]*pi/180;
      fi2:=(q[i]+nr[15+i])*pi/180;
      fi3:=nr[20+i]*pi/180;
      fi1p:=0; fi3p:=0; fi2p:=nr[5+i];
end
else
begin
if (nr[i]=1) then
begin
qgen[1+jj]:=nr[5+i]*tim; qgen[2+jj]:=0;qgen[3+jj]:=0;
fi1:=(q[i]+nr[10+i])*pi/180; fi2:=nr[15+i]*pi/180;
fi3:=nr[i+20]*pi/180; fi3p:=0;fi2p:=0;fi1p:=nr[5+i];
end
else
begin
fi1:=nr[10+i]*pi/180;
fi2:=nr[15+i]*pi/180;
fi3:=nr[i+20]*pi/180;
fi3p:=0;fi2p:=0;fi1p:=0;
end;
end;
end;
if i=1 then begin
s01[1,1]:=cos(fi3);
s01[1,2]:=sin(fi3);
s01[1,3]:=0;
s01[2,1]:=-sin(fi3);
s01[2,2]:=cos(fi3);
s01[2,3]:=0;
s01[3,1]:=0;
s01[3,2]:=0;
s01[3,3]:=1;
s01p[1,1]:=-fi3p*sin(fi3);
s01p[1,2]:=fi3p*cos(fi3);
s01p[1,3]:=0;
s01p[2,1]:=-fi3p*cos(fi3);
s01p[2,2]:=-fi3p*sin(fi3);
s01p[2,3]:=0;
s01p[3,1]:=0;
s01p[3,2]:=0;
s01p[3,3]:=0;
end
else begin if i=2 then
begin
s12[1,1]:=cos(fi2);
s12[1,2]:=0;
s12[1,3]:=-sin(fi2);
s12[2,1]:=0;
s12[2,2]:=1;
s12[2,3]:=0;
s2[3,1]:=sin(fi2);
s12[3,2]:=0;
s12[3,3]:=cos(fi2);
s12p[1,1]:=-fi2p*sin(fi2);
s12p[1,2]:=0;
s12p[1,3]:=-fi2p*cos(fi2);
s12p[2,1]:=0;
s12p[2,2]:=0;
s12p[2,3]:=0;
s12p[3,1]:=fi2p*cos(fi2);
s12p[3,2]:=0;
s12p[3,3]:=-fi2p*sin(fi2);
end
else
begin
if i=3 then
begin
s23[1,1]:=cos(fi2)*cos(fi3); s23[1,2]:=cos(fi2)*sin(fi3);
s23[1,3]:=-sin(fi2);s23[2,1]:=-sin(fi3);
s23[2,2]:=cos(fi3);s23[2,3]:=0;s23[3,1]:=sin(fi2)*cos(fi3);
s23[3,2] := sin(f2) * sin(f3); s23[3,3] := cos(f2);
s23p[1,1] := -f2p * sin(f2) * cos(f3) - f3p * cos(f2) * sin(f3);
s23p[1,2] := -f2p * sin(f2) * sin(f3) + f3p * cos(f2) * cos(f3);
s23p[1,3] := -f2p * cos(f2); s23p[2,1] := -f3p * cos(f3);
s23p[2,2] := -f3p * sin(f3); s23p[2,3] := 0;
s23p[3,1] := f2p * cos(f2) * cos(f3) - f3p * sin(f2) * sin(f3);
s23p[3,2] := f2p * cos(f2) * sin(f3) + f3p * sin(f2) * cos(f3);
s23p[3,3] := -f2p * sin(f2);
end
else
if i = 4 then
begin
s34[1,1] := cos(f2) * cos(f3);
s34[1,2] := cos(f2) * sin(f3) * cos(f1) + sin(f2) * sin(f1);
s34[1,3] := cos(f2) * sin(f3) * sin(f1) - sin(f2) * cos(f1);
s34[2,1] := -sin(f3);
s34[2,2] := cos(f3) * cos(f1);
s34[2,3] := cos(f3) * sin(f1);
s34[3,1] := sin(f2) * cos(f3);
s34[3,2] := sin(f2) * sin(f3) * cos(f1) - cos(f2) * sin(f1);
s34[3,3] := sin(f2) * sin(f3) * sin(f1) + cos(f2) * cos(f1);
s34p[1,1] := -f2p * sin(f2) * cos(f3) - f3p * cos(f2) * sin(f3);
s34p[1,2] := -f2p * sin(f2) * sin(f3) * cos(f1) + f3p * cos(f2) * sin(f1) + f1p * cos(f2) * sin(f3) - f2p * sin(f1) + f1p * sin(f2) * cos(f1);
s34p[1,3] := -f2p * sin(f2) * sin(f3) * sin(f1) + f3p * cos(f2) * cos(f3) * sin(f1) + f1p * cos(f2) * sin(f3) * cos(f1) - f2p * cos(f1) + f1p * sin(f2) * sin(f1);
s34p[2,1] := -f3p * cos(f3);
s34p[2,2] := -f3p * sin(f3) * cos(f1) - f1p * cos(f3) * sin(f1);
s34p[2,3] := -f3p * sin(f3) * sin(f1) + f1p * cos(f3) * sin(f1);
s34p[3,1] := f2p * cos(f2) * cos(f3) - f3p * sin(f2) * sin(f3);
s34p[3,2] := f2p * cos(f2) * sin(f3) * cos(f1) + f3p * sin(f2) * sin(f1) + f1p * sin(f2) * sin(f3) - f2p * cos(f1) + f1p * sin(f2) * sin(f1);
ANNEXE

\[\cos(\phi_3)\cos(\phi_1)-\phi_1p\sin(\phi_2)\sin(\phi_3)\sin(\phi_1)+\phi_2p\sin(\phi_2)\sin(\phi_3)\sin(\phi_1)-\phi_1p\cos(\phi_2)\cos(\phi_1)\]

s34p[3,3]:=\phi_2p\cos(\phi_2)\sin(\phi_3)\sin(\phi_1)+\phi_3p\sin(\phi_2)\cos(\phi_3)\sin(\phi_1)+\phi_1p\sin(\phi_2)\sin(\phi_3)\cos(\phi_1)-\phi_2p\sin(\phi_2)\cos(\phi_1)-\phi_1p\cos(\phi_2)\sin(\phi_1);
end
else
if i=5 then
begin
s45[1,1]:=-\phi_2p\sin(\phi_2)\cos(\phi_3)-\phi_3p\cos(\phi_2)\sin(\phi_3);
s45[1,2]:=-\phi_2p\sin(\phi_2)\sin(\phi_3)+\phi_3p\cos(\phi_2)\cos(\phi_3);
s45[1,3]:=-\phi_2p\cos(\phi_2);
s45[2,1]:=\phi_3p\cos(\phi_3);
s45[2,2]:=-\phi_3p\sin(\phi_3);
s45[2,3]:=0;
s45[3,1]:=\phi_2p\cos(\phi_2)\cos(\phi_3)-\phi_3p\sin(\phi_2)\sin(\phi_3);
s45[3,2]:=\phi_2p\cos(\phi_2)\sin(\phi_3)+\phi_3p\sin(\phi_2)\cos(\phi_3);
s45[3,3]:=-\phi_2p\sin(\phi_2);
end; end; end;
jj:=jj+3;
end;
mat(3,3,3,s12,s01,s02);
mat(3,3,3,s23,s02,s03);
mat(3,3,3,s34,s03,s04);
mat(3,3,3,s45,s04,s05);
mat(3,3,3,s12p,s01,s02p1);
mat(3,3,3,s12,s01p,s02p2);
ad(3,3,s02p1,s02p2,s02p);
mat(3,3,3,s23p,s02,s02p1);
mat(3,3,3,s23,s02P,s02p2);
ad(3,3,s02p1,s02p2,s03p);
mat(3,3,3,s34p,s03,s02p1);
mat(3,3,3,s34,s03P,s02p2);
ad(3,3,s02p1,s02p2,s04p);
mat(3,3,3,s45p,s04,s02p1);
mat(3,3,3,s45,s04p,s02p2);
ad(3,3,s02p1,s02p2,s05p);
w2[1,1]:=nr[27];w2[1,2]:=nr[28];
w3[1,1]:=nr[29];w3[1,2]:=nr[30];
w4[1,1]:=nr[29];w4[1,2]:=nr[30];
w5[1,1]:=nr[29];w5[1,2]:=nr[30];
mat(3,3,3,w2,s01,ad1);
mat(3,3,3,w3,S02,ad2);
ad(3,3,ad1,ad2,ad3);
mat(3,3,3,w4,s03,ad2);
ad(3,3,ad3,ad2,ad4);
mat(3,3,3,w5,s04,ad2);
ad(3,3,ad4,ad2,ad5);
mat(3,3,3,w5,s05,ad2);
ad(3,3,ad5,ad2,ad6);
for k:=1 to 3 do for m1:=1 to 3 do
s01t[k,m1]:=s01[m1,k];
for k:=1 to 3 do for m1:=1 to 3 do
s02t[k,m1]:=s02[m1,k];
for k:=1 to 3 do for m1:=1 to 3 do
s03t[k,m1]:=s03[m1,k];
for k:=1 to 3 do for m1:=1 to 3 do
s04t[k,m1]:=s04[m1,k];
for k:=1 to 3 do for m1:=1 to 3 do
s05t[k,m1]:=s05[m1,k];
mat(3,3,3,s01p,s01t,om01);
mat(3,3,3,s02p,s02t,om02);
mat(3,3,3,s03p,s03t,om03);
mat(3,3,3,s04p,s04t,om04);
ANNEXE

writeln; writeln; writeln;
writeln('Generalized co-ordinates'); writeln;
writeln(' \{ q \} R ');
window(20,11,50,26); textbackground(11);
textcolor(black); clrscr;
for i:=1 to 15 do
begin  gotoxy(8,i); writeln('q',i,'R=');
gotoxy(13,i); write(qgen[i]:11:6);
end;
window(22,28,50,30);
textbackground(lightgray);
textcolor(red); clrscr;
writeln; writeln(' \{ qd \} R '); window(20,31,50,46);
textbackground(yellow); textcolor(black); clrscr;
for i:=1 to 15 do
begin
  gotoxy(8,i); writeln('qd',i,'R=');
gotoxy(13,i); write(qrd[1,i]:10:3);end;
repeat a:=readkey until a=#27;
window(10,1,70,50);
textbackground(lightgray); clrscr;
textcolor(red); clrscr; writeln; writeln; writeln;
writeln('Co-ordinates of the origins of the own systems');
writeln;
writeln(' and co-ordinates of the final point of the link ');
writeln; writeln(' with respect to the absolute reference');

........................................
window(22,1,50,31); textbackground(lightgray);
textcolor(red); clrscr; writeln;
str2:='Angular speeds in the absolute co-ordinate system';
str1:= ' om1'; str3:= ' om2'; str4:= ' om3'; str5:= ' om4'; str6:= ' om5';
tab2(red,yellow,9,str1,str2,str3,str4,str5,str6,o1,o2,o3,o4,o5);
repeat delay(1) until readkey=#27; window(10,4,70,46);
texyred; clrscr; textcolor(red);
writeln(' Angular speeds in the own co-ordinate systems');
write(' om 

for j:=1 to 15 do ompt[1,j]:=omp[j,1];
aw2[1,2]:=0;aw2[1,3]:=w2[1,2];
aw2[2,1]:=0;aw2[2,3]:=-w2[1,1];
aw2[3,1]:=-w2[1,2];aw2[3,2]:=w2[1,1];
aw3[1,2]:=0;aw3[1,3]:=w3[1,2];
aw3[2,1]:=0;aw3[2,3]:=-w3[1,1];
aw3[3,1]:=-w3[1,2];aw3[3,2]:=w3[1,1];
aw4[1,2]:=0;aw4[1,3]:=w4[1,2];
aw4[2,1]:=0;aw4[2,3]:=-w4[1,1];
aw4[3,1]:=-w4[1,2];Aw4[3,2]:=w4[1,1];
aw5[1,2]:=0;aw5[1,3]:=w5[1,2];
aw5[2,1]:=0;aw5[2,3]:=-w5[1,1];
aw5[3,1]:=-w5[1,2];aw5[3,2]:=w5[1,1];
ar1[3,2]:=nr[31];ar1[2,3]:=-nr[31];
ar1[3,1]:=-nr[32];ar1[1,3]:=nr[32];
ar1[2,1]:=0;ar1[1,2]:=0;
ar2[3,2]:=nr[33];ar2[2,3]:=-nr[33];
ar2[3,1]:=-nr[34];ar2[1,3]:=nr[34];
ar2[2,1]:=0;ar2[1,2]:=0;
ar3[3,2]:=nr[35];ar3[2,3]:=-nr[35];
ar3[3,1]:=-nr[36];ar3[1,3]:=nr[36];
ar3[2,1]:=0;ar3[1,2]:=0;
ar4[3,2]:=nr[37];ar4[2,3]:=-nr[37];
ar4[3,1]:=-nr[38];ar4[1,3]:=nr[38];
ar4[2,1]:=0;ar4[1,2]:=0;ar5[3,2]:=nr[39];
ar5[2,3]:=-nr[39];ar5[3,1]:=-nr[40];
ar5[1,3]:=nr[40];ar5[2,1]:=0;ar5[1,2]:=0;

writeln( ' The coordinates of the centers of mass ');

tab1(white,5,red,str1,str3,str4,str5,str6,str2,s01p,s02p,
s03p,s04p,s05p);

mat(3,3,3,ar1,s01,mp1);
for i:=1 to 3 do for j:=1 to 3 do v1[i,j]:=mp1[i,j];
mat(3,3,3,aw2,s01,mp2);
mat(3,3,3,ar2,s02,mp6);
mat(3,3,3,aw3,s02,mp3);
mat(3,3,3,ar3,a03,mp8);
mat(3,3,3,aw4,s03,mp4);
mat(3,3,3,ar4,s04,mp10);
mat(3,3,3,aw5,s04,ad3);
mat(3,3,3,ar5,a05,ad4);
mat(3,3,3,aw5,s05,s02p1);
tab1(2,5,8,str1,str3,str4,str5,str6,str2,mp6,mp3,
mp4,mp10);
for i:=1 to 3 do for j:=1 to 3 do v2[i,j]:=mp2[i,j];
for i:=4 to 6 do for j:=1 to 3 do v2[i,j]:=mp6[i-3,j];
for i:=1 to 3 do for j:=1 to 3 do v3[i,j]:=mp2[i,j];
for i:=4 to 6 do for j:=1 to 3 do v3[i,j]:=mp3[i-3,j];
for i:=7 to 9 do for j:=1 to 3 do v3[i,j]:=mp8[i-6,j];
for i:=1 to 3 do for j:=1 to 3 do v4[i,j]:=mp2[i,j];
for i:=4 to 6 do for j:=1 to 3 do v4[i,j]:=mp3[i-3,j];
for i:=7 to 9 do for j:=1 to 3 do v4[i,j]:=mp4[i-6,j];
for i:=10 to 12 do for j:=1 to 3 do v4[i,j]:=mp10[i-9,j];
for i:=1 to 3 do for j:=1 to 3 do v5[i,j]:=mp2[i,j];
for i:=4 to 6 do for j:=1 to 3 do v5[i,j]:=mp3[i-3,j];
for i:=7 to 9 do for j:=1 to 3 do v5[i,j]:=mp4[i-6,j];
for i:=10 to 12 do for j:=1 to 3 do v5[i,j]:=ad3[i-9,j];
for i:=13 to 15 do for j:=1 to 3 do v5[i,j]:=ad4[i-12,j];
for i:=1 to 3 do for j:=1 to 3 do v6[i,j]:=mp2[i,j];
for i:=4 to 6 do for j:=1 to 3 do v6[i,j]:=mp3[i-3,j];
for i:=7 to 9 do for j:=1 to 3 do v6[i,j]:=mp4[i-6,j];
for i:=10 to 12 do for j:=1 to 3 do v6[i,j]:=ad3[i-9,j];
for i:=13 to 15 do for j:=1 to 3 do v6[i,j]:=s02p1[i-12,j];
for k:=1 to 15 do ompt[1,k]:=omp[k,1];
mat1(1,15,3,ompt,v1,vit1);
mat1(1,15,3,ompt,v2,vit2);
mat1(1,15,3,ompt,v3,vit3);
mat1(1,15,3,ompt,v4,vit4);
mat1(1,15,3,ompt,v5,vit5);
mat1(1,15,3,ompt,v6,vit6);
window(1,1,75,45); textbackground(7);
clrscr; writeln; writeln; textcolor(red); writeln;
writeln('                  The speeds of the centres of mass');
setgraphmode(gm);
closegraph;
end.

procedure tab1(n,p,m1:integer;str1,str3,str4,str5,str6,str2:
string;
mp1,mp2,mp3,mp4,mp5:t1);
begin
clrscr;
window(1,1,79,79);
textbackground(lightgray); clrscr;
window(12,10,60,15);
textbackground(lightgray);
textcolor(P); clrscr;
writeln(str2); writeln; writeln;
window(10,15,70,45);
textbackground(M1); clrscr; writeln; writeln;
textcolor(P); writeln(str1); textcolor(N);
for i:=1 to 3
do begin
  writeln;
  for j:=1 to 3 do
    write('       ',mp1[i,j]:10:3);
end;
writeln; writeln; writeln; textcolor(P);
writeln(str3); textcolor(N);
for i:=1 to 3 do begin
  writeln;
  for j:=1 to 3 do
    write('       ',mp2[i,j]:10:3);
end;
writeln; writeln; writeln; textcolor(P);
writeln(str4); textcolor(N);
for i:=1 to 3 do begin
  writeln;
  for j:=1 to 3 do
    write('       ',mp3[i,j]:10:3);
end;
writeln; writeln; writeln;
textcolor(P); writeln(str5);
textcolor(N);
for i:=1 to 3 do begin
  writeln;
  for j:=1 to 3 do
    write('       ',mp4[i,j]:10:3);
end;
writeln; writeln; writeln;
textcolor(P); writeln(str6); textcolor(N);
for i:=1 to 3 do begin
writeln;
for j:=1 to 3 do
   write('       ',mp5[i,j]:10:3);
end;
repeat a:=readkey until a=#27;
end;

procedure tab2 (n,m1,p:integer;str1,str2,str3,
    str4,str5,STR6:string;mp1,mp2,mp3,mp4,mp5:t);
begin
   clrscr;
textbackground(lightgray); window(5,10,79,15);
textbackground(lightgray);
textcolor(n); clrscr; writeln(str2);writeln;
window(10,15,70,45); textbackground(p);
textcolor(m1);
clrscr;
i:=1;
writeln; writeln;writeln; writeln; writeln;
for j:=1 to 3 do
   write(str1,j,'=',mp1[i,j]:10:3);
writeln; writeln;writeln;writeln;writeln;
for j:=1 to 3 do
   write(str3,J,'=',mp2[i,j]:10:3);
writeln; writeln; writeln; writeln; writeln;
for j:=1 to 3 do
   write(str4,J,'=',mp3[i,j]:10:3);
writeln; writeln; writeln; writeln; writeln;
for j:=1 to 3 do
   write(str5,j,'=',mp4[i,j]:10:3);
writeln; writeln; writeln; writeln; writeln;
for j:=1 to 3 do
   write(str6,J,'=',mp5[i,j]:10:3);
writeln; writeln;
repeat a:=readkey until a=#27;
end;

procedure mat(n,m1,p:integer;a1,b1:t1;var c1:t1);
begin
i:=0;
while i<n do
begin i:=i+1;j:=0;
while j<p do
begin j:=j+1;k:=0;c1[i,j]:=0;
while k<m1 do
begin     k:=k+1;
c1[i,j]:=c1[i,j]+a1[i,k]*b1[k,j];
end;
end;
end;
end;

procedure mat1(n,m1,p:integer;a1:sss;b1:sss;var c1:t);
begin
i:=0;
while i<n do
begin i:=i+1;j:=0;
while j<p do
begin j:=j+1;k:=0;c1[i,j]:=0;
while k<m1 do
begin     k:=k+1;
c1[i,j]:=c1[i,j]+a1[i,k]*b1[k,j];
end;
end;
end;

procedure ad(n,p:integer;a1,b1:t1;var c1:t1);
begin
for n:=1 to n do for p:=1 to p do c1[n,p]:=a1[n,p]+b1[n,p];
end;

procedure tas_trei(aa:char;nr_comp:integer;poz:integer);
var bb,ccc:char;
begin
gotoxy(length(m[poz])+1,poz);
textbackground(red);
textcolor(white+blink);
write(nr[poz]:11:6);
textcolor(white);
repeat bb:=readkey until (bb=chr(72)) or (bb=chr(27)) or (bb=chr(13));
if (bb=#72) or (bb=#13) then begin
  move2(bb,nr_comp,poz);
  if bb=chr(13) then
  begin
    gotoxy(length(m[wherey])+1,wherey);
    textcolor(white);i:=wherey;read(nr[i]);
    gotoxy(length(m[wherey-1])+1,wherey-1);
    textcolor(white+blink);
    write(nr[i]:11:6);reset(f1);seek(f1,i-1);
    write(f1,nr[i]);close(f1);
  end;
  repeat ccc:=readkey;
  move2(ccc,nr_comp,poz);
  if ccc=chr(13) then begin
    gotoxy(length(m[wherey])+1,wherey);
    textcolor(white);i:=wherey;read(nr[i]);
    gotoxy(length(m[wherey-1])+1,wherey-1);
    textcolor(white+blink);
    write(nr[i]:10:3);reset(f1);seek(f1,i-1);
    write(f1,nr[i]);
    close(f1);
  end;
until ccc=chr(27);
end;
end;

procedure ini_fis(nume_fis:string;poz,nr_comp:integer);
begin
  textbackground(lightgray); textcolor(white); clrscr;
  assign(f1, nume_fis);
  {$I-}
  reset(f1);
  {$I+};
  if ioresult <> grok
  then
    begin
      write('The file is not on the disk'); readln;
      clrscr; rewrite(f1); textmode(259);
      textbackground(lightgray); clrscr; textcolor(white);
      for i:=1 to nr_comp do
        begin
          write(m[i]); read(nr[i]); write(f1,nr[i]);
        end;
    end;
  else
    begin
      textmode(259); textbackground(lightgray); clrscr;
      textcolor(white);
      i:=1;
      repeat
        read(f1,nr[i]);
        i:=i+1;
      until eof(f1);
      close(f1);
      for j:=1 to i-1 do
        writeln(m[j],nr[j]:10:3);
    end;
  end;

procedure move2(tl:char;nr_comp:integer;poz:integer);
begin
cc:=length(m[wherey])+1;
if (ord(tl)=72) and (wherex > cc) then
begin
if (wherey > 1) and (wherey <= nr_comp) then
begin
textbackground(white);
gotoxy(length(m[wherey])+1,wherey);
textcolor(white);
write(nr[wherey]:11:6);
gotoxy(length(m[wherey-1])+1,wherey-1);
textbackground(red);
textcolor(white+blink);
write(nr[wherey]:11:6);
end; end
else
if (ord(tl)=80) and (wherex > cc) then
begin
if (wherey >=1) and (wherey < nr_comp)
then
begin
textbackground(white);
gotoxy(length(m[wherey])+1,wherey);
textcolor(white);
write(nr[wherey]:11:6);
gotoxy(length(m[wherey+1])+1,wherey+1);
textbackground(red);
textcolor(white+blink);
write(nr[wherey]:11:6);
end;
end;
end;
{5.5 PROGRAM FOR A COMPUTATIONAL ANALYSIS OF PRESSED CURVE D - AFFECTED BY THE PRINCIPLE OF MOVEMENT INVERSION}

uses crt,dos,graph;
const detect=0;
type mm=array[1..6] of string[50];
nn1=array[1..6] of integer;
vec=array[0..360] of real;
veec=array[0..360] of integer;
const m:mm= ('length of AB element        ',
'length of BC element        ',
'length of CD element        ',
'x of point D                ',
'y of point D                ',
'n of driver element');
var pif,ppif,xe,ye:real;
fl:file of integer;
nr:nn1;vf3,vf2:vec;
vpx,vpy:veec;
aa:char;
fi1,lab,lbc,lcd,n1,xb,yb,fi2,fi3,a,b,c,xd,yd,xc,yc,pix:real;
fi2p,fi3p,fi2pp,fi3pp,xcp,ycp,xcpp,ycpp:real;
fi1p,xbp,ybp,xbpp,ybpp,t1,t2,xdp,ydp,xdpp,ydpp:real;
gd,gm,i,j,coo,co:integer;
{$i abel.pas}{$i labd10.pas}
{main program}
begin
initgraph(gd,gm,'c:\bp\bgi');
if graphresult <> 0 then writeln(GraphErrorMsg(graphresult));
cleardevice;
setbkcolor(white);
settextstyle(3,horizdir,1);setcolor (magenta);
Program for a computational analysis of pressed curve D'
affected by the principle of movement inversion.

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if ioresult <> grok then
begin
rewrite(f1);
for i:=1 to 6 do begin
write(m[i]);
read (nr[i]); write(f1,nr[i]);
end;
close (f1);
repeat delay(5) until readkey=#27;
end
else
begin
for i:=1 to 6 do
begin
read(f1,nr[i]); writeln(m[i],nr[i]:10);
end;
close(f1);
repeat delay(5) until readkey=#13;
end;
lab:=nr[1]; lbc:=nr[2]; lcd:=nr[3]; xd:=nr[4]; yd:=nr[5]; n1:=nr[6];
fi1:=0.;
for i:=0 to 360 do
begin
fi1:=i;
abel(fi1,lab,n1,xb,yb,fi1p,xbp,ybp,xbpp,ybpp);
{clrscr;
writeln('xb=',xb,'yb=',yb,'xbp=',xbp,'ybp=',ybp,'xbpp=',xbpp,'yb
pp=',ybpp); repeat aa:=readkey until aa=#27;}
xdp:=0; ydp:=0;
labd10(i,pix,xb,yb,xd,yd,xbp,ybp,xbpp,ybpp,xdp, ydp,xdpp, ydp
p,lbc,lcd,xc,yc,fi2,fi3,a,b,c,fi2p,fi3p,fi2pp,fi3pp,xcp,ycp,xcpp,
ycpp);
pix:=fi3; vf3[i]:=pix; vf2[i]:=fi2;
{writeln('ung.elem.3=',vf3[i]*180/pi);readln;}
end;
setgraphmode(gm);
co:=trunc(getmaxy*5/6); coo:=trunc(getmaxx/4);
cleardevice;
setviewport(1,1,getmaxx,10+2*textwidth('P'),false);
setbkcolor(white); setcolor(blue); settextstyle(3,horizdir,3);
settextjustyfy(centertext,toptext);
outtextxy(getmaxx div 2,5,' The pressed curve D' );
outtextxy(getmaxx div 2,5+textwidth('P'),'generated by the
four bars mechanism');
setviewport(1,5+2*textwidth('P')+2, getmaxx,getmaxy,false);
co:=co-5-2*textwidth('P');
i:=0;
repeat
if i > 360 then begin pif:=vf3[i-trunc(i/360)*360+1];
ppif:=vf2[i-trunc(i/360)*360+1];
end
else begin pif:=vf3[i];
ppif:=vf2[i];
end;
x:=2*lbc*cos(ppif); y:=2*lbc*sin(ppif); setcolor(magenta);
{for j:=1 to 2 do begin}
line(coo,co,coo+trunc(lab*cos(i*3.141592/180)),co-
    trunc(lab*sin(i*3.141592/180)));
moveto(coo+trunc(lab*cos(i*3.141592/180)),co-
    trunc(lab*sin(i*3.141592/180)));
lineto(coo+trunc(lab*cos(i*3.141592/180)+x),co-
    trunc(lab*sin(i*3.141592/180)+y));
line(coo+trunc(xd),co,coo+trunc(xd+lcd*cos(pif)),co-
    trunc(lcd*sin(pif)));
circle(coo,co,3);circle(coo+trunc(xd),co,3);
circle(coo+trunc(lab*cos(i*3.141592/180)),co-
    trunc(lab*sin(i*3.141592/180)),3);
circle(coo+trunc(xd+lcd*cos(pif)),co-trunc(lcd*sin(pif)),3);
line(coo,co+3,coo+trunc(10*cos(225*pi/180)),co+3-
    trunc(10*sin(225*pi/180)));
moveto(coo+trunc(10*cos(225*pi/180)),co+3-
    trunc(10*sin(225*pi/180)));
linerel(13,0);lineto(coo,co+3);
line(coo+trunc(xd),co+3,coo+trunc(xd)+trunc(10*cos(225*pi/180)),co+3-
    trunc(10*sin(225*pi/180)));
moveto(coo+trunc(xd)+trunc(10*cos(225*pi/180)),
    co+3-trunc(10*sin(225*pi/180)));
linerel(13,0);lineto(coo+trunc(xd),co+3);
ANNEXE

line(coo+trunc(10*cos(225*pi/180)),co+3-trunc(10*sin(225*pi/180)),co+trunc(15*cos(225*pi/180)),co+3-trunc(15*sin(225*pi/180)));
line(coo+trunc(10*cos(225*pi/180))+7,co+3-trunc(10*sin(225*pi/180)),coo+trunc(15*cos(225*pi/180))+7,co+3-trunc(15*sin(225*pi/180)));
line(coo+trunc(10*cos(225*pi/180))+13,co+3-trunc(10*sin(225*pi/180)),coo+trunc(15*cos(225*pi/180))+13,co+3-trunc(15*sin(225*pi/180)));
line(coo+trunc(10*cos(225*pi/180))+trunc(xd),co+3-trunc(10*sin(225*pi/180)),coo+trunc(15*cos(225*pi/180))+trunc(xd),co+3-trunc(15*sin(225*pi/180)));
line(coo+trunc(10*cos(225*pi/180))+trunc(xd)+7,co+3-trunc(10*sin(225*pi/180)),coo+trunc(15*cos(225*pi/180))+trunc(xd)+7,co+3-trunc(15*sin(225*pi/180)));
line(coo+trunc(10*cos(225*pi/180))+trunc(xd)+13,co+3-trunc(10*sin(225*pi/180)),coo+trunc(15*cos(225*pi/180))+trunc(xd)+13,co+3-trunc(15*sin(225*pi/180)));

for j:=0 to 360 do
begin
xe:=2*lbc*cos(vf2[j]);ye:=2*lbc*sin(vf2[j]);
vpx[j]:=coo+trunc(lab*cos(j*pi/180)+xe);
vp[y][j]:=coo-trunc(lab*sin(j*pi/180)+ye);
putpixel(vpx[j],vpy[j],red);
end;
if i=0 then
repeat delay(1) until readkey=#27;clearviewport;
i:=i+5;
until keypressed;
closegraph;
end.
restart;
rb:=143.7793; re:=163.2978; rd:=155.213; sd:=13.1686;
teta:=1; alfa:=20; xc:=0; yc:=0; ri: 145.5146;
psi:= 360*Pi/ (38*180); i:=1;
rtet[i]:=evalf(i*teta*Pi/180);
vect[i]:=evalf(rb*sqrt(1+rtet[i]**2));
for i from 1 by 1 while vect[i]<=re do
xb[i]:=evalf(vect[i]*sin(rtet[i]-arctan(rtet[i],1))+xc);
yb[i]:=evalf(vect[i]*cos(rtet[i]-arctan(rtet[i],1))+yc);
rtet[i+1]:=evalf((i+1)*teta*Pi/180);
vect[i+1]:=evalf(rb*sqrt(1+rtet[i+1]**2));
od;
ung:=evalf(arctan(sqrt(re**2-rb**2)/rb,1));
ung1:=evalf(sin(ung)/cos(ung)-ung);
ex1:=evalf(re*sin(ung1)+xc);
Ye1:=evalf(re*cos(ung1)+yc);
cod:=evalf(2*(sin(alfa*Pi/180)/(cos(alfa*Pi/180))-
alfa*Pi/180)+sd/rd);
xd:=evalf(rb*sin(cod)+xc);
yd:=evalf(rb*cos(cod)+yc);
i:=1;
rtet[ii]:=evalf(ii*teta*Pi/180);
vect[ii]:=evalf(rb*sqrt(1+rtet[ii]**2));
for ii from 1 by 1 while vect[ii]<=re do
xf[ii]:=evalf(vect[ii]*sin(arctan(rtet[ii],1)-rtet[ii]+cod)+xc);
yf[ii]:=evalf(vect[ii]*cos(arctan(rtet[ii],1)-rtet[ii]+cod)+yc);
rtet[ii+1]:=evalf((ii+1)*teta*Pi/180);
vect[ii+1]:=evalf(rb*sqrt(1+rtet[ii+1]**2));
od;
t1:=[seq([xb[k],yb[k]],k=1..30)];
t2:=[seq([xf[31-k],yf[31-k]],k=1..30)];
ex2:=evalf(re*sin(cod-ung1)+xc);
ye2:=evalf(re*cos(cod-ung1)+yc);
t3:=[op(t1),[xe1,ye1],[xe2,ye2],op(t2)];
vxb[1]:=xc;
vyb[1]:=rb+yc;
for j from 2 by 1 to i do
  vxb[j]:=xb[j-1];
  vyb[j]:=yb[j-1];
  od;
  vxb[j]:=xe1;
  vyb[j]:=ye1;
  vxf[1]:=xe2;
  vyf[1]:=ye2;
  for j from 2 by 1 to ii do
    vxf[j]:=xf[31-(j-1)];
    vyf[j]:=yf[31-(j-1)];
    od;
    vxf[j]:=xd;
    vyf[j]:=yd;
  for kk from 0 to 37 do
    for i from 1 to 32 do
      vxbb[kk,i]:=evalf((vxb[i]-xc)*cos(2*Pi-psi*kk)-(vyb[i]-yc)*sin(2*Pi-psi*kk)+xc);
      vybb[kk,i]:=evalf((vxb[i]-xc)*sin(2*Pi-psi*kk)+(vyb[i]-yc)*cos(2*Pi-psi*kk)+yc);
      vxff[kk,i]:=evalf((vxf[i]-xc)*cos(2*Pi-psi*kk)-(vyf[i]-yc)*sin(2*Pi-psi*kk)+xc);
      vyff[kk,i]:=evalf((vxf[i]-xc)*sin(2*Pi-psi*kk)+(vyf[i]-yc)*cos(2*Pi-psi*kk)+yc);
      od;
      od;
  for kkk from 0 to 37 do
tt1[kkk]:=[seq([vxbb[kkk,m],vybb[kkk,m]],m=1..32)];
tt2[kkk]:=seq([vxff[kkk,n],vyff[kkk,n]],n=1..32]);
tt3[kkk]:=[op(tt1[kkk]),op(tt2[kkk])];
od;
tt4:=[op(tt3[0],op(tt3[1],op(tt3[2]),op(tt3[3]),op(tt3[4]),op(tt3[5]),op(tt3[6]),op(tt3[7]),op(tt3[8]),op(tt3[9]),op(tt3[10],op(tt3[11]),op(tt3[12]),op(tt3[13]),op(tt3[14]), op(tt3[15]),op(tt3[16]), op(tt3[17]), op(tt3[18]), op(tt3[19]), op(tt3[20]), op(tt3[21]), op(tt3[22]), op(tt3[23]), op(tt3[24]), op(tt3[25]), op(tt3[26]), op(tt3[27]), op(tt3[28]), op(tt3[29]), op(tt3[30]), op(tt3[31]), op(tt3[32]), op(tt3[33]), op(tt3[34]), op(tt3[35]), op(tt3[36]), op(tt3[37])]);
plot(tt4,scaling=constrained);

............................
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