

TRIZ APPLICATION IN DEVELOPMENT OF CLIMBING ROBOTS

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ABSTRACT

Paper is devoted to consideration of the practical application of the Algorithm of Inventive Problem Solving (ARIZ) during the development process of the robot adaptive vacuum feet. Also TRIZ technology evolution trends have been used for development of the new structures of the autonomous climbing robot. These robots are being used for cleaning, finishing and diagnostics of arbitrarily oriented surfaces in space for instance shop windows, glass vestibules, nuclear reactor walls and oil tank surfaces. The new designs of the vacuum adaptive feet and climbing robots have been developed with the aid of applied ARIZ and other TRIZ tools. The specific schemes and designs of vacuum adaptive feet and robots are described. The new vacuum feet can operate on many different surfaces including uneven and cracked ones. This paper has been illustrated with the pictures of real robots and their performances. The outcome of this project was 20 patents with the application of some of them in the current robot's design. This paper is useful for TRIZ users who like a real case study with measured results and demonstrate how TRIZ was used to develop the solutions.

INTRODUCTION

This publication continues line of papers [3, 4] integrating author's knowledge on the practical application of basic TRIZ tools used in real-life projects. Particularly, ARIZ application in mechanical engineering design in different actual practices of mass-production company, a consulting firm, university's scientific laboratory is accumulated in these articles. Successful and unsuccessful sometimes experience of applying TRIZ gives potential to summarize some material for future improvement of methodology's tools by analysis of specific practical projects.

The paper consists of two parts. The first part is devoted to practical application of ARIZ85B for development and improvement of new robot's vacuum adaptive feet which capable to operate on the cracked surface. The main problem of solving process in this part was to develop new concept designs providing reliable work of vacuum robot's foot on cracked surfaces which destroys vacuum.

The second part of paper dedicated to practical application of TRIZ evolution trends or patterns to development of new vacuum wall-climbing robot's designs. The main goal of that process is to obtain such robot's designs that are able to work like autonomous vehicles with good parameters of controllability and manoeuvrability and without connection by pipes and lines with land-based power supply equipment.

This project was implemented during several years in Saint-Petersburg State Technical University [4, 5] and has been supported by Ministry of Science and Technical Politics of Russian Federation, Saint-Petersburg Subway, State Research Russian Centre of Robotics and Technical Cybernetics, Nuclear Power Plant and other organizations.

Numerous vacuum climbing robots were produced for different purposes during this project period. In the first part of paper we focused on the specific designs of vacuum feet for windows cleaning and washing. It was first direction, which started this project.

PART 1. ARIZ DEVELOPMENT OF ADAPTIVE FEET

The Algorithm of Inventive Problem Solving (ARIZ) [1] application for the development of new vacuum feet designs for climbing robot is described in this part of paper. Specifically, improvement of vacuum suction mechanism is considered, which provides the reliable vacuum adhesion of the robot to different working surfaces. For this given problem, ARIZ85B [2] was used and basic logical procedures used are briefly explained.

The first part of algorithm requires analysis of the problem, development of the problem statement and transition from the problem with an indefinite inventive situation to an extremely simple model of the problem. The second part of ARIZ helps to analyze of the problem's model and define product, tool, supersystem and environment substances and field resources used during solving process. The third part, images of Ideal Final Result and Physical Contradiction are formulated. These definitions guide us to a complete set of breakthrough solutions. The forth part continues transformation from problem to solutions based on the physics by mobilization and utilization of existent system resources. The goal of the fifth part is development of new concept of solutions by utilization of the information databases.

1.1. PROBLEM STATEMENT

1.1.1. The Robot's Features

Described in this paper, climbing robots have a wide application of use in many areas (Fig 1):

- at home for vacuum cleaning and washing of windows and walls;
- for municipal needs, cleaning of the glass walls in subway stations, airports, shops, offices, hospitals, hotels;
- in shipbuilding for cleaning and repairing of the ship's and submarine's hulls from algae and mineral formations;
- in nuclear industry for examining the internal structures of nuclear reactor walls and for diagnostics.

The climbing robot is retained to and moves along the working surface using vacuum feet. The simplified step robot's structure includes at least two vacuum feet (Fig.2), connected with help of a linear motor and rotary motor. Linear motor can be made like a pneumatic



Fig.1. Robot-cleaner for windows

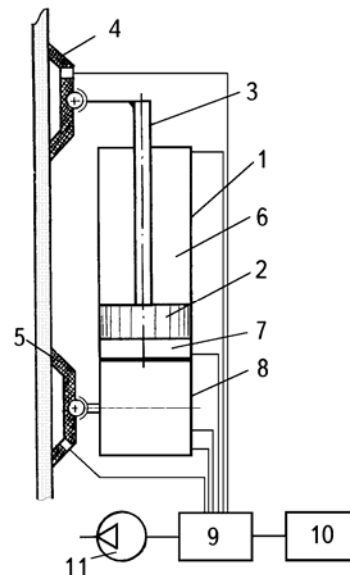


Fig.2. Simplified scheme of the double-foot wall-climbing vacuum robot

driver that contains cylinder 1 with piston 2 and rod 3. The rod 3 is jointed to first vacuum foot 4. The second vacuum foot 5 is coupled with the rotary air motor 8 that is connected to the cylinder 1. For creation of the negative pressure the vacuum pump 11 is used. The negative pressure is distributed between vacuum feet and motors by valve unit 9 managed by control system 10.

The climbing robot is installed on the window surface and under vacuum is kept on it. For starting of the linear motion, under foot 5 a large vacuum is created. At the same time into foot 4 control system 10 and valve unit 9 generate a small vacuum. Therefore, foot 5 is fixed on the surface by bigger vacuum and friction force and other foot 4 is moved ahead by moving out rod 3 of cylinder 1. It is the first step. During the next step, the vacuum values under the feet are changed in opposite direction: under foot 5, a small vacuum and under foot 4, a big vacuum is created. Therefore, foot 4 is fixed onto the surface and foot 5 is drag up by moving cylinder 1. So the robot slides ahead step by step.

The robot has a rotary drive 8 to change the direction of movement. In that case, vacuum foot 5 is fixed on the cleaned surface and drive 8 rotates linear drive 1 with foot 4 to a new direction.

The robot design can be made like an autonomous vehicle with onboard electrical batteries, vacuum pump and a control system with an infrared receiver. The operator installs the mobile module on the working surface and turns on the remote infrared control system.

1.1.2. The Robot Foot's Structure and Principle

As mentioned before, for movement of the robot on a cleaned window surface, two vacuum feet are used 4 and 5 (Fig.1). The vacuum under foot is created by small-sized vacuum pump 1 (Fig.2). The small-sized vacuum pump 1 can be located directly on the foot's body 2. The vacuum foot has an elastic seal 3 which contacts with the cleaned glass surface 4. Vacuum is generated under the foot by a vacuum pump and holds the robot on the cleaned glass surface during its motion from one position to other one. If the glass surface doesn't have any defects, the vacuum foot works well. But if on the glass surface there is a defect 5 (crack, orifice, irregularity, etc.), the efficiency of the vacuum foot is compromised. The inner vacuum of the foot is depressurized by leakage of atmospheric air through the defect.

To compensate for the leak and preservation of the vacuum under the foot, engineers tried to apply a high-power vacuum pump. But the overall dimensions and weight of foot and robot are greatly increased. Therefore, the robot's manoeuvrability and productivity become worst.

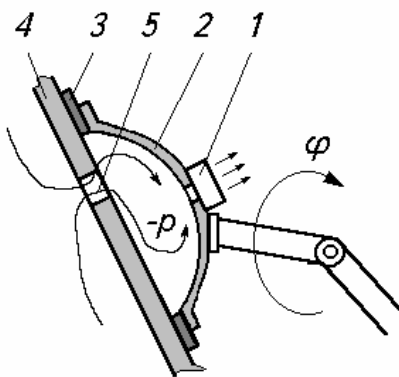


Fig.3. Scheme of the robot vacuum foot

Engineers tried to use another way for solving the described problem. They placed the high-power pump not on the foot and robot's body but separate from the robot. In this case, it was proposed to connect foot and vacuum pump by using additional flexible pipelines. As result, weight and overall dimensions of the robot's mobile part have been decreased but it's manoeuvrability and productivity remained low due to loss of the robot's autonomy and other troubles from long umbilical cord. Another big disadvantage of this design was the loss of vacuum pressure in the connective pipeline, which increased the need for a larger pump.

It is necessary to save the existing vacuum operating method of the foot and robot with the glass surfaces and to offer solutions to overcome the problems described above.

1.2. ANALYSIS OF THE PROBLEM

Mini-problem: The technical system called vacuum foot of the robot for vacuum cleaning of glass surface includes the foot body, vacuum pump, elastic seal, glass surface and crack on the surface.

The Technical Contradiction (TC)-1: If we use high-power vacuum foot in our design, it provides a good vacuum adhesion of the foot to a cracked glass surface but increases overall dimensions and mass of the vacuum pump.

The Technical Contradiction (TC)-2: If we use low-power vacuum foot in our design, it does not increase dimensions and mass of the vacuum pump but it does not produce the required vacuum value under foot and adhesion during work with a cracked glass surface.

It is necessary with minimum modifications of existing system to provide reliable adhesion of the vacuum foot to the cracked glass surface and to keep the small dimensions and mass of the vacuum pump.

Conflicting pair: The products are a cracked glass surface and the vacuum pump; tool is the vacuum foot.

The graphic schemes of TC-1 and TC-2 are represented in Fig. 4.

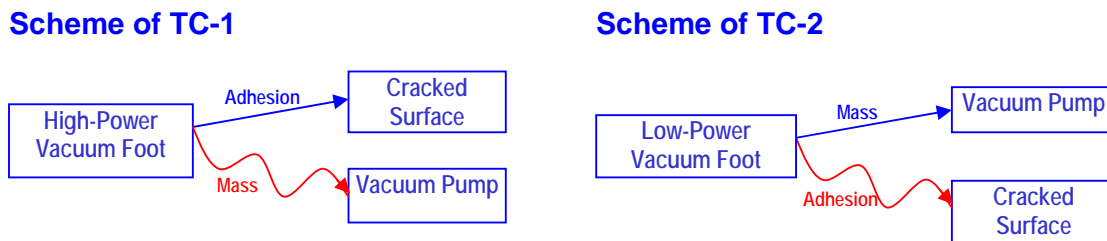


Fig.4. The graphic schemes of TC-1 and TC-2

As a main parameter we selected small overall dimensions and mass of applied vacuum pump and therefore use the low-power vacuum foot. Why do we select this parameter? Because we are planning to mainly use this robot in home conditions, which requires easy utilization. Therefore the scheme of the second conflict TC-2, for our further analysis, is selected. Here we only note that TC-1 scheme could also be resolved as separate task.

Intensified conflict: in according with a classical variant ARIZ-85B, we should replace “low-power vacuum foot” by “zero-power vacuum foot” and formulate intensified conflict for considered case like foot with “zero vacuum” eliminates vacuum pump and so decreases mass of robot (excellent !), but does not produce any adhesion between foot and cracked glass surface (bad !).”

“Intensified conflict” is one of the strong points of ARIZ85B but it is not irreproachable, to our mind. From the standpoint of “pure science” this formulation is a good one because it leads to creation of a powerful, new concept of solution. It becomes the base of a new physical operating principle for improving the system. If we have no hard limitations of time for research, development, production and money for such a new product, we could go this way.

Typically, applied science and practical activities in manufacturing conditions require another approach. Factory and especially company with mass-production agreed with changes for manufactured articles only in special case with “super profit”. It happens very rarely. It is clear because modification of only one procedure for a new product in the whole technology process can cost a lot of money. Therefore, if a proposed solution should be introduced in a production line in a short time without long debates then the best way is to save the existing physical principle and try to improve the existing product with the smallest modification. In fact, this is correlated with IFR formulation.

Turning back to our problem, formulation of intensified conflict leads to a modification of the applied vacuum principle by utilisation of other non-vacuum schemes and physical methods (for instance, magnetic, electrostatic, electrochemical, and etc.) for creation of adhesion between foot and surface. We are subject to a condition of our initial task and will save the existing operating vacuum method of the foot and robot with the glass surfaces.

The model of our problem looks as follows:

Conflicting pair - a cracked glass surface is the product and foot with low-power vacuum is the tool.

Formula of a conflict: the foot with low-vacuum power does not increase mass of pump and of robot (excellent!) but it does not produce adhesion between foot and cracked glass surface (bad!).

What should X-element do for problem solving: X-element should provide vacuum adhesion between the foot and the cracked surface without increasing vacuum and the mass of foot and robot.

Utilization of standards: For solving of our formulated problem in the above model, we can use Standard 1.1.2, which can be transformed, for our specific case to provide a good vacuum adhesion. An additional substance, S3, should be introduced inside vacuum foot (Substance S1) or into cracked glass surface (Substance S2). We can show the diagram for this transformation which shown on Fig. 5.

On this stage, we find out some general answers and directions for solving our problem: “Add SOMETHING (X-element) to the foot design OR to the cracked glass surface for solving of our problem”. Now it is difficult to imagine what we can specifically add or how to modify the vacuum foot (because in fact, we can change only this element). We can keep this recommendation and will try to develop the specific solutions in the next part of ARIZ.

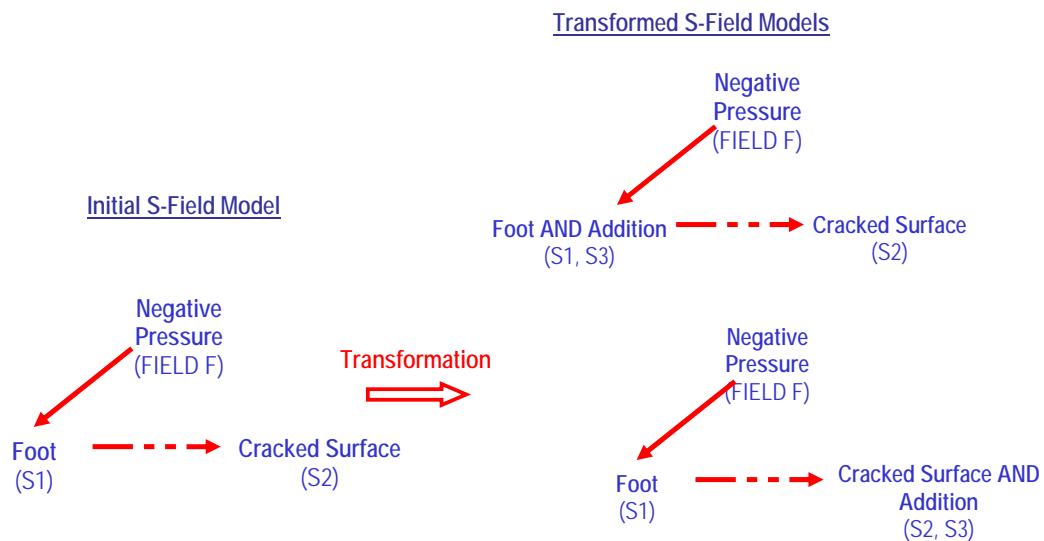


Fig.5. Utilization of Standard Solutions and transformation of initial S-Field model

1.3. ANALYSIS OF THE PROBLEM'S MODEL

Operating zone (OZ): An operating zone is area near to a crack under foot and outside (Fig. 6).

Operating time (OT): It is the time of vacuum adhesion on a cracked glass surface by the vacuum foot.

Substance and Field Resources:

Resources of the **vacuum foot** as tool:
 plastic body, elastic seal, negative pressure, normal force between seal and glass, frictional force.

Resources of the **glass surface** as product:
 glass surface, crack, air stream.

Resources of **supersystem and environment:**
 robot's equipment, ambient air, atmospheric pressure, gravitational and geomagnetic fields.

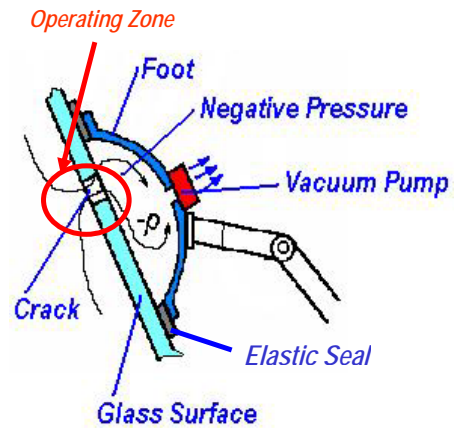


Fig.6. Operating Zone

1.4. IDEAL FINAL RESULT AND PHYSICAL CONTRADICTION DETERMINATION

The Ideal Final Result (IFR)-1: X-element eliminates negative pressure decreasing under vacuum foot at the crack's zone (OZ) during vacuum suction (OT) without making the system more complex and without increasing the suction power and the mass of the system.

Intensified IFR-1: It is impossible to enter into the system any new substances and fields, and the X-element should be discovered from available resources. And so, the vacuum foot ITSELF (without using any foreign or new field and substances) eliminates negative pressure drop under vacuum foot in the crack's zone (OZ) during vacuum suction (OT) without making the system more complex and without increasing the suction power and the mass of the system.

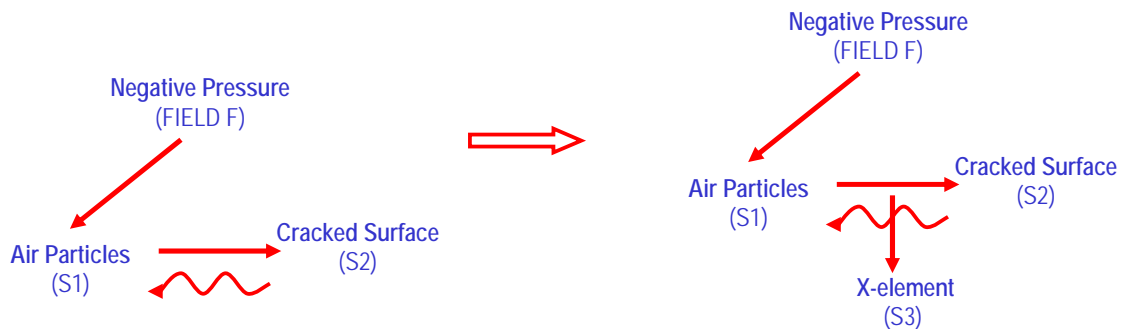


Fig.7. Utilization of Standard Solutions for IFR-2 solving

The Physical Contradiction on macro-level (macro-PhC): The operating zone under the vacuum foot near from crack in the glass surface during suction process should have negative pressure to provide vacuum adhesion between foot and surface and should have no negative pressure (should have atmospheric pressure) because of atmospheric air leaks under pressure differential through the crack and the vacuum foot.

The Physical Contradiction on micro-level (micro-PhC): Air particles should not be under vacuum foot near to a crack during suction process for providing negative pressure AND should be because ambient air streams through the crack.

IFR-2: The area under the foot along a crack and near (OZ) during adhesion process (OT) ITSELF provides opposite physical conditions (presence and absence of atmospheric air particles): atmospheric air particles of that flow through crack should be ITSELF transformed into “vacuum particles”.

Utilization of Standard Solutions for IFR-2 solving: We can use Standard 1.2.1 from first group, as above, which leads us to the next general proposal: for providing good vacuum adhesion an additional subject S3 (free of charge!) should be introduced between air particles under negative pressure (“vacuum particles”) and cracked surface with atmospheric ambient air, as shown in Fig.7.

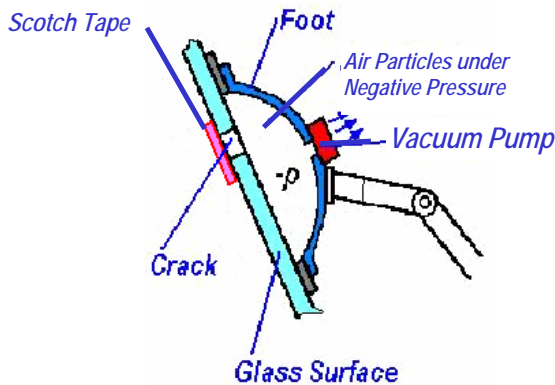


Fig.8. Concept 1: new substance S3 introduction

After application of this standard’s formulation, we obtain the first partial concept of solution (Fig. 8). It is proposed to use in advance, inexpensive Scotch tape (or paper) which will close the crack and placed between vacuum foot and cracked surface. This tape may be placed in opposite side of cracked glass surface as shown in the diagram.

In fact, conceptually we are solving our physical problem but practically of course, this proposal cannot satisfy us. We may evaluate this solution concept as a “warm-up” for other, stronger concepts of solution.

1.5. MOBILIZATION AND UTILIZATION OF RESOURCES

Application of Small Smart People Modelling Method

Let’s represent atmospheric air particles streaming through a crack in the glass surface like dark small people and vacuum particles on other side of surface like gray small people.

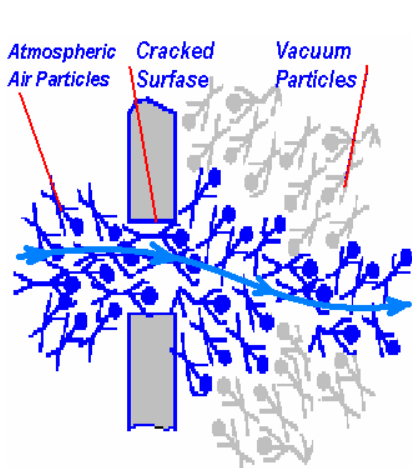


Fig. 9. Application of a method of simulation by small people.
The initial scheme of a conflict.

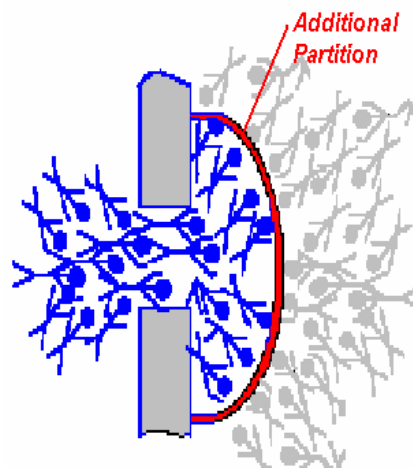


Fig. 10. Application of a method of simulation by small people.
One of the schemes for resolving the conflict.

In the first scheme (Fig. 9), the conflict is represented: atmospheric air “dark small people” run through crack in a glass surface and than displace vacuum “gray small people”. Atmospheric air “dark small people” is much stronger than vacuum “gray small people”. Therefore, “dark small people” press and displace “gray small people”.

How to eliminate this fight between the two groups of “small people”? The simple solution comes to mind is to install some barrier between them. In the next scheme (Fig. 10), one of the scenarios for resolving of the conflict is shown. Between the two fighting groups of small people an additional partition is being used. There is no direct contact between the two groups and therefore the strong atmospheric air “dark small people” cannot directly interact with weak vacuum “gray small people”.

This scheme gives us the next idea: to use a separating diaphragm and to make the foot a multi-sectional design (Fig. 11).

The new foot has body 1, designed as a frame. Within the frame are located numerous vacuum sectional mini-feet 2. Each mini-foot is supplied with elastic diaphragms 3 and are connected by common vacuum pump. The system is installed on a surface 4 and a vacuum in the chambers of feet is formed. Under operation of vacuum, the elastic deformation of diaphragms occurs, as it is shown in Fig. 11.

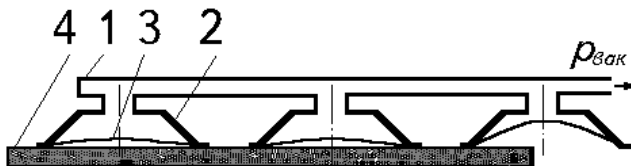


Fig. 11. Concept of solution 2: Multisectional vacuum foot with separating diaphragms [6]

The diaphragm deformation leads to increasing of the volume between diaphragm 3 and surface 4, and therefore to making of vacuum. This vacuum leads to adhesion of the mini-feet to a glass surface.

The vacuum mini-feet that are not placed on a surface (on Fig 11 - on the right) or are located on a surface with a crack don't deactivate the rest of the system. These mini-feet don't have an influence on the other working vacuum mini-feet and are excluded automatically from work of the whole system.

Depressurization of other vacuum mini-feet does not happen because they are separated from ambient atmospheric air by the diaphragm and the whole foot continues to operate reliably.

Thus proposed concept solution (Fig. 11) satisfies both contradictory parts of the macro physical contradiction and IFR-1, because elastic diaphragm (X-element) eliminates negative pressure fall under vacuum foot in the crack zone (OZ) during vacuum suction (OT) with minimum changes of the system and without increasing suction power and mass of the system.

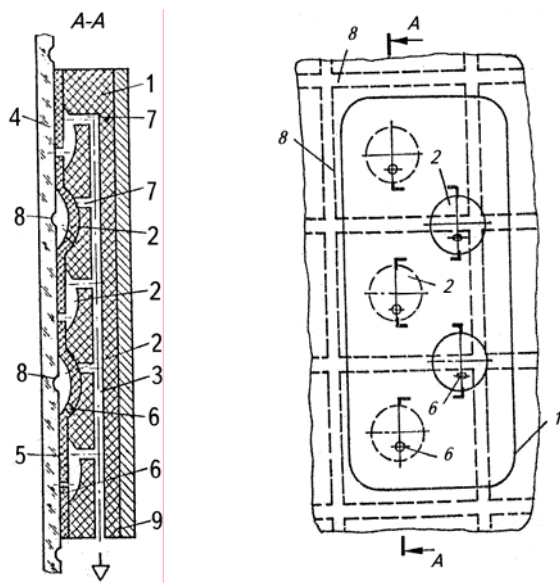
Nevertheless we would like to continue our work with ARIZ and hope to develop other new solutions and designs of our robot foot.

Method "Step Back From IFR": it is proposed to represent future result with minimum deviations from IFR. As indicated in IFR-1 above, foot with the low-power vacuum is reliably fixed on a surface with a crack and leakage through a crack doesn't depressurize the system. Let's make a step back from that IFR and imagine that there is a small leakage of air through the vacuum foot that is then eliminated by foot.

The realisation of this mental experiment leads us to idea of making a small hole in the diaphragm in each section of the previous design of vacuum foot. We are getting a new construction of foot in Fig. 12, with new useful properties.

The system has body 1 with vacuum mini-chambers 2 connected by a vacuum line 3 with a vacuum pump. From the side of cleaning surface 4 on the body 1, the flexible diaphragm 5 is fixed. In diaphragm 5, small orifices 6 are made. Orifices 6 don't match with orifices 7 into the body 1. The surface 4 can have a smooth flat surface and surface with recesses 8. Foot body 1 is fastened on supporting plate 9.

The foot is placed on surface 4 and is engaged. Air from vacuum chambers 2 through orifices 7 and vacuum line 3 are evacuated. In vacuum, mini-chambers that are placed on a smooth surface 4 without recesses 8 (for example, first, third and fifth mini-chambers from above Fig. 12), a vacuum is formed.



**Fig. 12. Concept of solution 3:
Multisectioal vacuum foot
with a small hole in the diaphragm [7]**

In vacuum mini-chambers 2, placed on surface 4 with recess 8 (for example, second and fourth mini-chambers from above in Fig. 12), a vacuum is not formed. In these mini-chambers through recesses 8 the atmospheric air flows under pressure difference.

Orifices 6 are made to a small diameter (about a millimetre) and are capable of leaking only a small volume of air. Therefore, the pressure difference is created on each diaphragm. This pressure curves diaphragms 5 in the direction of vacuum chamber 2 and press onto the wall of the chamber.

Orifices 6 and 7 are disconnected and indicated vacuum chambers 2 placed on the recesses 8 automatically are closed. Depressurization of other vacuum chambers on the foot does not happen and the robot continues to work reliably.

In vacuum mini-chambers 2 (first, third and fifth from above in Fig. 12), there is no air suction through recesses 8. In these mini-chambers there is only a small leakage through contact between diaphragm 5 and smooth surface 4. Therefore, this air leakage easily flows through orifices 6 and doesn't curve diaphragm 5.

Using orifices in diaphragm provides new useful properties to the foot in comparison with previous design. The new foot can provide cleaning and evacuation dust particles through diaphragm orifices from the surface together with vacuum adhesion and so combines several functions at the same time.

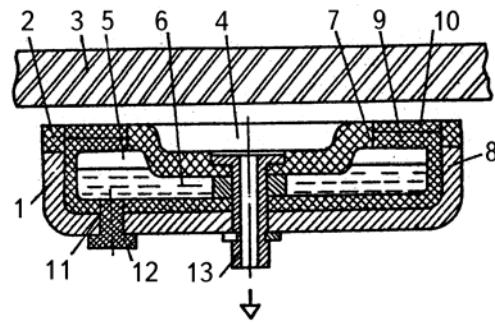
Thus proposed concept solution (Fig. 12) also satisfies both contradictory parts of the macro-physical contradiction and IFR-1. The elastic diaphragm with holes (X-element) eliminates negative pressure fall under vacuum foot in the crack zone (OZ) during vacuum suction (OT) with minimum changes to the system and without increasing suction power and mass of the system.

Application of mixture of resource substances:

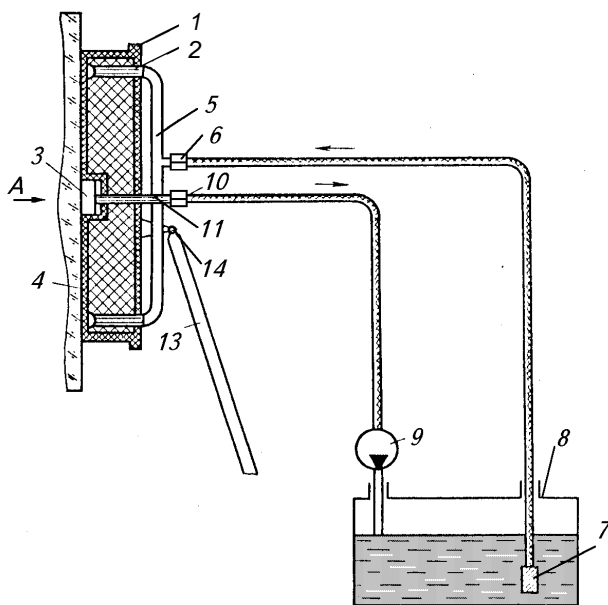
During analysis of resource substances and their mixture on this step, there was an idea to use an air stream through a crack for making a vacuum. There are well-known systems in which a vacuum is produced by air streams, for instance, sprays, ejectors, etc. If it would be possible to use this resource then it would be possible to transform a harmful phenomenon into a benefit and allows us to apply a strong and beautiful inventive principle to the problem. How to do this one? Let's pass to the next procedures of the algorithm but we mark the possibility of using an air stream to produce a vacuum.

Application of hollow or mixture of resource substances with a hollow (to use of porous structures: foam, air bubbles, etc.):

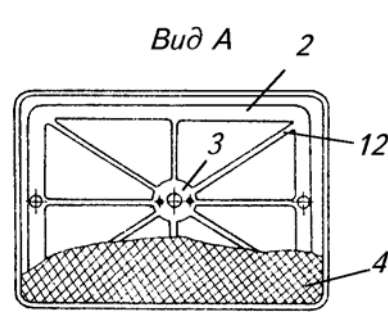
Mental experiments on this step leads to making of an elastic seal such as a sponge impregnated with a liquid, for example, water. The use of water allows considerably increasing "leakproofness" because the water closes micro-irregularities in a zone of a seal in contact with a surface. This property is a very important thing especially when the vacuum foot needs to move along a rough surface, for instance, a concrete wall. It was proposed for the new design of the foot (Fig. 13) and to use an inexpensive resource like water 6, inside vacuum foot 1. Sponge 9 supplies water on the working foot surface 10.



**Fig. 13. Concept solution 4:
Vacuum foot for concrete surface [8]**



**Fig. 14. Concept of solution 5:
Vacuum foot for cleaning of rough surface [9]**



Using water greatly improves the contact area between foot 1 and rough surface 3 and eliminates the leakage between them. It is especially useful for working with concrete surfaces or other rough surface because water closes microasperities on the concrete surface and eliminates negative pressure reduction between vacuum foot and surface.

It has been proposed additionally (Fig.14) to move water by vacuum and to provide cleaning and evacuation of dust particles from the surface together with vacuum. Then the water is cleaned from dust particles by filter 7 and returned to cleaned surface 4.

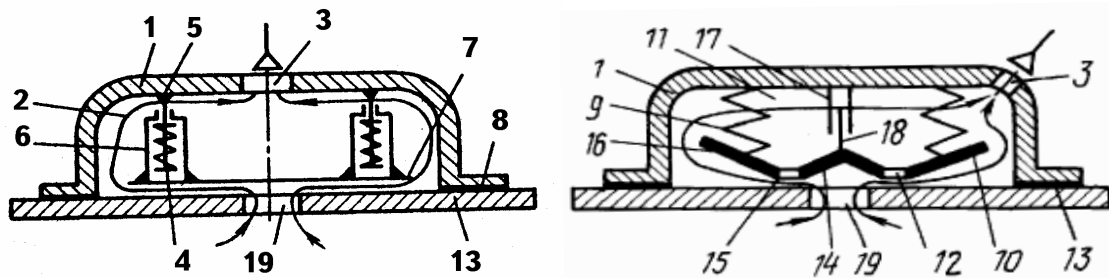
Application of a mixture from existing resource substances with "hollow": In our problem "hollow" is the vacuum so we already have applied and considered this before.

Application of an electrical field or interaction of two electrical fields: In our case to add electrical fields is not suitable because we can seriously complicate all system.

1.6. UTILIZATION OF THE INFORMATION DATABASE

Application of physical effects and phenomena database to resolve micro-PhC and to achieve IFR-2: First of all, we remember that we have a "draft idea" to use an air stream through a crack to produce a vacuum. Let's find the section of physics: "Hydro- and gas-dynamics", and then find Bernoulli's law which states: where the stream velocity is higher, the static pressure is lower.

For getting negative pressure near glass surface it is necessary to speed up air stream. It can be done by various design methods. We will use IFR-principle: "vacuum foot itself..."



**Fig. 15. Concept of solution 6:
Vacuum foot with the flat floating disk [10]**

Different designs of such a vacuum foot are shown in Fig. 15 above.

The foot contains body 1 with vacuum chamber 2 connected through orifice 3 with the vacuum pump (is not shown). In chamber 2, there are elements 4 that are made like springs. These are placed between guide rods 5 and cylinders 6. Rods 5 are fixed to body 1, and cylinders 6 are fixed on the flat disk 7. The flat disk 7 is located parallel to glass surface 13. Thus disk 7 is installed with the possibility of sliding along guide rods 5.

The foot is placed on glass surface 13. Through an orifice 3, the vacuum pump produce vacuum in a chamber 2. If surface 13 doesn't have a hole or crack 19, the system works as a typical vacuum foot.

If surface 13 has a hole or crack 19, system works as follows. Through crack 19, the air stream is formed. The direction of movement of this stream is shown in the figure by arrows. Since formed clearance between a flat surface 3 and flat disk 7 is small, significant acceleration of an air stream occurs here. Increasing the velocity leads to a pressure decrease in the clearance area. The flat disk 7 and glass surface 13 are being attracted. Clearance between surface 13 and disk 7 is being decreased more and air stream velocity with dynamic vacuum is being increased more. Finally, the stabilisation of a clearance and value of dynamic vacuum between the disk 7 and surface 13 is reached.

Thus airflow from crack creates vacuum between flat disk 7 and glass surface 13. Disk 7 is attracted to surface by dynamic vacuum between them and holds whole foot body 1 by way of cylinder 6, spring 4 and rod 5. This concept design transforms harmful phenomena (air leakage through crack) into the benefit (vacuum creation) and strong inventive principle “Blessing in Disguise” is realised.

The level of vacuum between the disk 7 and surface 13 can be adjusted by a modification of the clearance area, square and shape of flat disk 7 (see Fig 15, on the right), productivity of the vacuum pump, and on the sectional area of orifice 19.

Thus the proposed concept of solution (Fig. 15) satisfies both contradictory parts of the micro-physical contradiction and IFR-2, because atmospheric air particles in flow through crack are ITSELF transformed into “vacuum particles”. This Bernoulli’s phenomenon eliminates negative pressure fall under vacuum foot in the crack zone (OZ) during vacuum suction (OT) with minimum changes of the system and without increasing the suction power and mass of the system.

PART 2. TRIZ EVOLUTION TRENDS IN DEVELOPMENT OF CLIMBING ROBOT

It is known from classical TRIZ that technical systems evolve in predictable patterns. Each of the patterns is called a "line" or a “trend” of evolution. There are 8 trends of evolution [1]:

1. Completeness and Life Cycle of Technical Systems
2. Energetic Conductivity of System
3. Transition to Synchronization (matching/mismatching)
4. Increasing of System Ideality
5. Uneven development of subsystems
6. Transition to a super- or subsystem’s levels (Mono-Bi-Poly-Systems)
- 6.a. Dynamization
7. Transition to microlevel using energy fields
8. Increasing the system S-Field development

G. Altshuller classified these trends in three groups, which were called: “statics” (trends 1-3), “kinematics” (4-6,a) and “dynamics” (7,8). Statics describes period of birth and forming of technical system. Kinematics trends defines period of system’s growth and development. Dynamics trends are related to the concluding period of a system’s development and transition to a new system.

Technical systems follow these general trends. From the initial system to multiple improvements, the system always moves towards Ideality until exhaustion of the existing technology and system’s resources. Upon discovery and application of new technology, the system will continue to evolve towards its final goal of Ideality.

These 8 trends of evolution provide the paths that a technical system travels during it’s lifespan. Each path gives the system degrees of freedom to grow and to move closer to Ideality [5].

In this part, we will explore how TRIZ technology evolution and forecasting trends have been used to solve 12 problems in the development of the new structures of the mobile autonomous robot module. We will use just five trends:

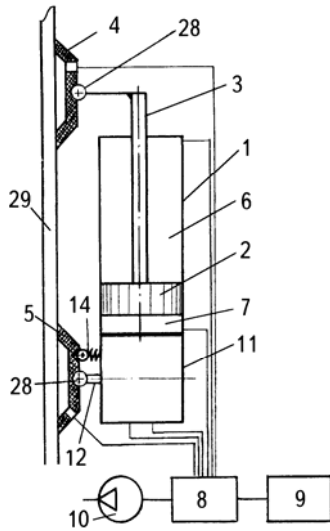


FIG. 16..
The vacuum wall-climbing robot with two pneumatic drive. Design version 1 [12]

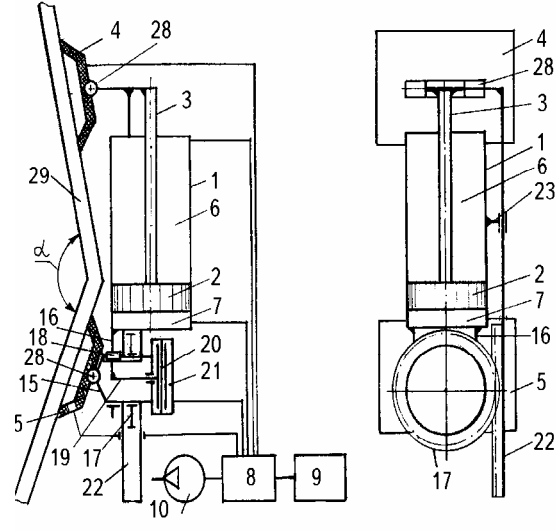


FIG. 17. Application of TRIZ Ideality Principle.
The vacuum wall-climbing robot with one pneumatic drive. Design version 2 [12]

- Increasing of System Ideality Trend (problems 1 – 5)
- Transition to a Supersystem and Mono-Bi-Poly Evolution Trend (problem 6)
- Dynamization Trend (problem 7)
- Transition to microlevel using energy fields (problem 8)
- Increasing S-Field development trend (problem 9-12)

2.2. TRIZ IDEALITY TREND APPLICATION

In accordance with the TRIZ Ideality Principle, the ideal system performs its functions without a system (system is absent). Therefore any technical system throughout its life tends to become more simple, effective, reliable, i.e. more ideal. Ideality always reflects maximum utilization of existing resources. In this project several ways have been used to make this robot a more ideal technical system:

- utilize internal and external resources that already exist or easily available for new robot's functions
- increase the amount of useful functions of the system
- transfer as many functions as possible to the feet which produce the robot's final action
- transfer some function of the robot to the supersystem or to the outside environment.

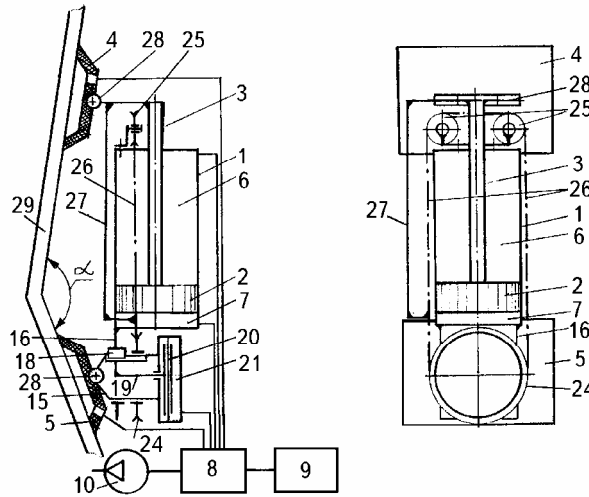
PROBLEM SOLVING 1. Typically, compressed air is used for operation of the robot. Compressed air is supplied in chambers of the linear and rotary drives and through ejectors in gripper cameras. The ejector transforms flow of air into a vacuum. The effectiveness of ejectors is low and its application leads to power losses. Engineers tried to replace ejectors, but then it would be necessary to use two different power sources (instead of one). One source is an air compressor which creates compressed air. The other one is a vacuum pump for creation of negative pressure under the feet. Each solution complicates the design of the robot:

During implementation of this project, TRIZ principle of Ideality had been used. Obviously, in correspondence with this principle only one type of driving pressure should be use in the robot. So only vacuum should be used both for robot's feet and for the robot's drives. The examples of such robots are represented on fig. 2.

The first robot's design uses the rotary vacuum mechanism for turning of robot in a new direction (fig. 16). The body 11 of given drive is joined with the cylinder 1, and its output shaft 12 has the vane 13 and connects with vacuum foot 5. The body 11 of rotary drive through the clamper 14 is also connected with vacuum foot 5.

PROBLEM SOLVING 2. The previous design uses a driving vacuum for both linear and rotary drivers and also for vacuum feet. Could we increase ideality of robot by elimination of one of the drives? For instance, can rotary one delegate its rotary functions to linear drive? This robot's design without a rotary vacuum drive is shown in fig. 17: rotary vacuum drive does not exist but its functions are performed.

FIG. 18
Application of TRIZ Ideality Principle.
The vacuum wall-climbing robot with flexible linkage between linear drive and vacuum clutch. Design version 3 [12]

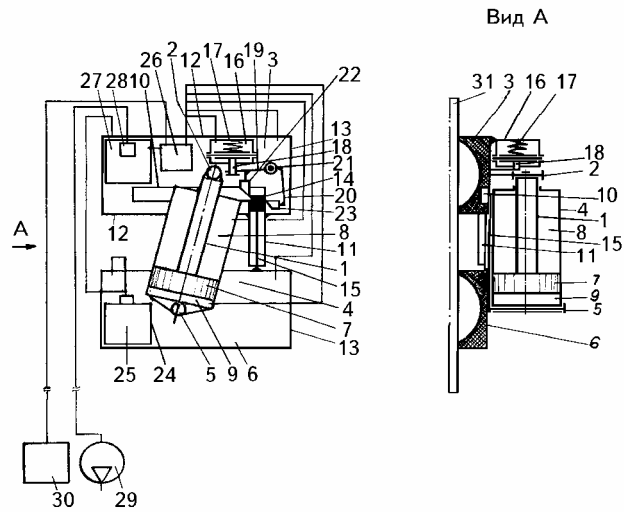


In this construction, the rotation is carried out by the linear drive with the help of the rotary clutch 15. This design has significant advantages in comparison with previous one. The clutch does not use any friction seals like the rotary drive and so there is no power losses due to friction. The other improvement of the new design is that there is no vacuum leakage through the moving parts in comparison with robot on fig.16. The clutch's operation is carried out through membrane drive 20 and closed vacuum chamber 21 without any leakage and friction. Robot's rotation is realized by linear drive 1 which rotates robot around fixed foot 5 through clutch 15 which interacts by rack 22.

PROBLEM SOLVING 3. Using the rack in the construction shown in fig.17 leads to increasing the weight and overall dimensions of the robot. Could we increase ideality of robot once again by elimination of this rack while keeping its driving function? It was proposed to make "flexible rack", which leads to concept of design with application instead of a rack with a belt-drive, chain-drive or cord linkage 26 (fig.18). As a result of weight and dimensions of the robot are improved.

PROBLEM SOLVING 4. Another example of applying the TRIZ Ideality Principle for improvement of the robot's design with just one linear drive is shown in fig. 19. The new design also has only one linear drive but can realize travel on a plane in two coordinates. For moving in the second coordinate, a special motor isn't used. For this purpose the mechanism of plane clutch 16 with the drive from a linear motor 4 is applied. This clutch also uses vacuum and membrane drive for switching of robot's direction of motion.

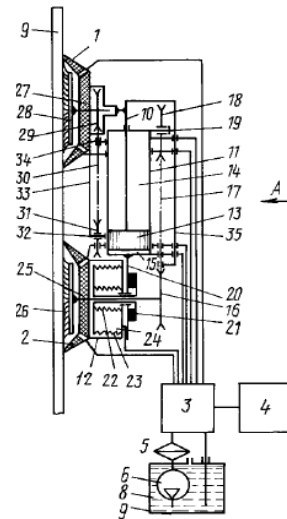
FIG. 19
Application of TRIZ Ideality Principle.
The vacuum wall-climbing robot with one linear drive and two-coordinate motion. Design version 4 [13]



In the considered engineering solutions, the number of motors and amount of weight are reduced and their function of motion are performed.

PROBLEM SOLVING 5. The vacuum wall robots that were previously discussed are designed for better utilisation of internal and external resources that existed in the system or were readily available. As mentioned before, another way for increasing ideality is to transfer as many functions as possible to the feet which produce the robot's final action.

FIG. 20
Application of TRIZ Ideality Principle.
The vacuum wall-climbing robot with multifunctional feet. Design version 5 [14]



It was proposed to improve the cleaning robot's function by using brushes 26 and 28 under vacuum feet 2 and 1. Cleaning rotation of these brushes is carried out from linear drive 11 without the application of additional motors. Thus, cleaning parameters of the robot are improved with minimal changes in the design. The robot's feet carry out several functions simultaneously: providing of vacuum keeping for robot and motion on the surface; circulation of washing solution on surface; additional mechanical cleaning of the surface with brushes using. So we use this way for increasing of robot's ideality by transferring of additional functions to vacuum foot.

2.2. UTILIZATION OF MONO-BI-POLY EVOLUTION TREND

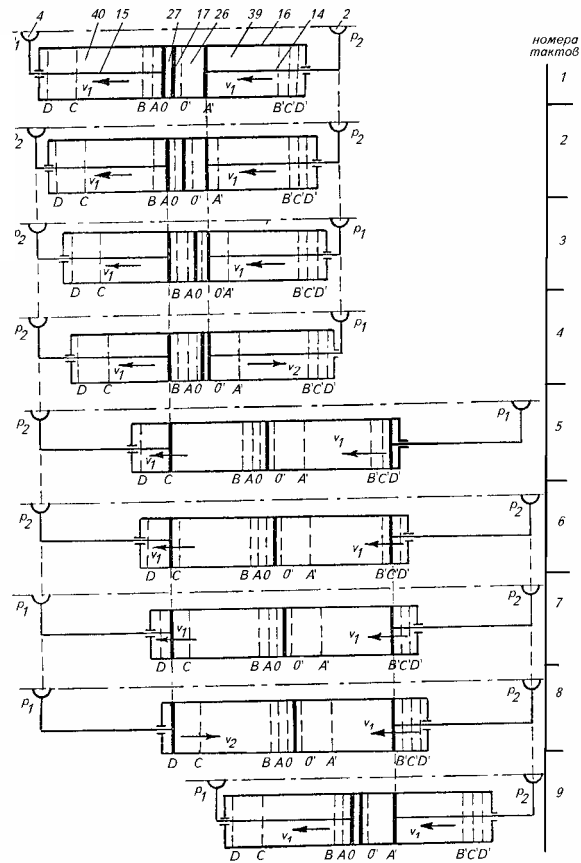
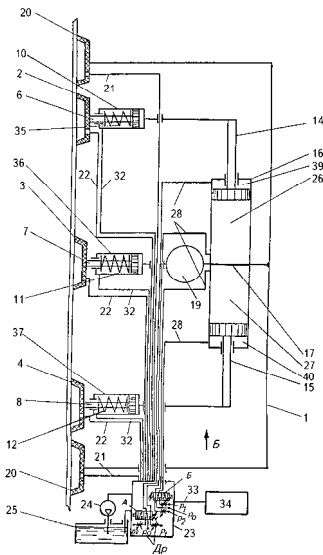
Having exhausted the possibilities of further development, a system is included in a supersystem as one of its parts. In so doing, further development takes place at the supersystem level. The simplest way for this development as a trend is the integration of similar systems in the line of "mono-bi-poly"

and obtaining a new synergy effect. The new problem solving and development of a new system with a new synergy effect is the base of the application this evolution trend as presented below.

PROBLEM SOLVING 6. The above vacuum wall robots are designed on the basis of the linear vacuum drive that are realized step-by-step (discrete) moving of the robot. Such design has an essential disadvantage that leads to possibility of short-term stops of the body and technological tool on it during movement. This feature is a negative attribute for using the robots for welding or painting of surfaces. Even short-term stops of a technological tool together with the robot's body are unacceptable as it leads to poor operation quality. It is necessary to save the simple discrete vacuum drive but to provide non-stop moving with this drive.

FIG. 21
The scheme of the wall-climbing robot with the linear vacuum drive and with non-stop moving [15]

FIG. 22
The cyclogram of movement of the wall-climbing robot with linear discrete vacuum drive and non-stop moving



For solving this problem, it was proposed to use TRIZ Mono-Bi-Poly evolution trend and unite two linear drives together as shown in fig 21.

The result of the application of this evolution trend is the development of the new robot's design with non-stop moving and the conservation of simple vacuum linear drives. That design is presented in fig. 6. The key of this scheme is using the double linear vacuum drive and transition to supersystem.

The cyclogram of movement of the wall-climbing robot with linear discrete vacuum drive and non-stop moving is shown in fig.7.

In this diagram, the motion of this robot resembles the motion of man with two feet which are stopped by in turn without the body stopping. When one foot 4 is stopped, the other foot 2 together with double cylinder 16 is moved. Then foot 2 is being adhered to working surface and foot 4 moves

together with double cylinder's body 16. Thus robot's body makes non-stop one-direction movement with a constant velocity v_1 . This non-stop movement is transmitted to a processing tool 20 which is fastened with a double cylinder through body 1. As a result, body 1 together with the processing tool 20 move without stopping and with constant speed v_1 .

2.3. UTILIZATION OF DINAMIZATION TREND

Dynamization trend states that in the course of evolution, a technical system develops from a rigid structure into a flexible or jointed system. The use of dynamization leads the system to a higher level of Ideality and provides new useful functions to the system.

Dynamization of the system, as rule, provides for better efficiency and control of the system. In accordance with this trend dynamization can go beyond one hinge design, many hinges, flexible form to liquid and gas and then to plasma and physical field. Additionally, the system can also become more dynamic at the field level – from continuous effect to impulse effect.

Using this trend for robot's design has led to improvement of features and increasing of robot's functionality. Only one example with application of dynamization trend for problem solving 7 is considered.

PROBLEM SOLVING 7. The first models of the climbing robot had rigid body's structure and the vacuum feet were jointed to a rigid body as well. This robot can move only on a flat surface and cannot move on profiled surface therefore the design had limited functional features. To overcome this limitation it was proposed to use additional hinges between the body's elements and the body and other parts, i.e. to apply dynamization trend. In the new design, the robot's body is connected to the feet with the aid of additional hinges 28 (fig. 18). Also, the vacuum clutch 21 has a function of a hinge and foot 5 can rotate in other direction. This makes the previous problem solvable and the robot obtains additional adjustable properties to move on profiled surface 29.

2.4. TRANSITION TO MICROLEVEL USING ENERGY FIELDS

This type of evolution is characterized not by making something small but rather by performing the function by using alternative energy fields in a more efficient way. The transition from macro to micro level is one of the main if not the strongest tendency in the evolution of technical systems. At some point in time, any further development of the macro system is useless. A new way must be found so that the function of the old system is carried out by molecules, atoms or electrons.

This trend has been applied for the improvement of the robot's foot operating principle of cleaning and led to the development of the new foot's design with additional physical function and new performances. That example with the application of transition to microlevel using resource energy field for problem solving 8 is analyzed.

PROBLEM SOLVING 8. As described before (see problem solving 5) for cleaning of surfaces rotary brushes are being used. Brushes are rotated through a mechanical transmission line by a linear drive during the robot's motion, i.e. mechanical energy for the cleaning process is utilized. Utilization of mechanical energy and transmission complicates the robot's design and produces negative effects. The mass of the robot is increased and reliability is reduced. So we are at a point in the design development of the robot when any further modification of the system on the macro level is almost useless. It is a good indicator to stop and to think of how to use another physical way to solve the problem with application of another resource. Consider using substances and fields of the vacuum foot on other micro level by particles or molecules for cleaning.

It is proposed to use the physical phenomena of “cold boiling” of liquid at low temperature under negative pressure and the creation of hydrodynamic cavitation. In vacuum the foot under negative

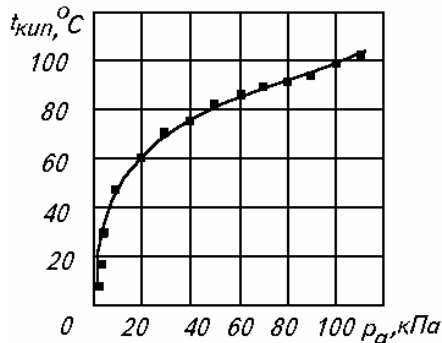
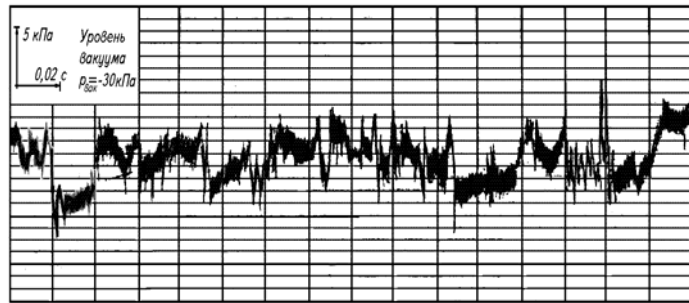


FIG. 23

Correlation between boiling temperature and ambient pressure for water

FIG. 24

Experimental oscillogram of pressure change under cavitation



pressure -90 kPa (absolute pressure is 10 kPa), “cold boiling” comes at a temperature of 28-30C degree (fig. 23). A cavitation is the formation and disappearance of bubbles (caverns) in a liquid. This is caused by a micro local change in pressure. If the micro local pressure falls below the vapor saturation pressure, then cavitation nuclei (bubbles) are formed in the liquid. When the micro local pressure increases, the bubbles collapse abruptly. This causes the propagation of a pressure pulse in the form of a shock wave in the surrounding medium (fig. 24).

In hydrodynamic calculations nondimensional parameter named cavitation constant is used. This constant is defined as

$$\chi = \frac{p_1 - p_{sv}}{\rho v^2 / 2},$$

where p_1 and v – absolute pressure and flow speed under vacuum feet, p_{sv} and ρ - saturation vapor pressure and liquid density.

The amount of χ , at which the cavitation process can begin, is the cavitation critical constant χ_{cr} . This parameter depends from local hydrodynamic resistance and specific liquid performances.

By changing indicated parameters, particularly pressure and flow rate, it is possible to control the cavitation process. It is a good physical principle for cleaning under the vacuum foot and all necessary resources (negative pressure, washing solution, and hydrolines) have already performed in the existing system. Just the operating cleaning zone under the vacuum foot should be designed for directional and controlled action of the hydrodynamic cavitation.

It was proposed that for practical realization of this cleaning physical mechanism between cleaned surface 4 (fig. 14) and foot surface 1, we would need to make a flat slot gap for liquid to flow under vacuum and the creation of good conditions for cavitation. Cavitation in this passage of the vacuum foot produces cavitation bubbles which collapse with original noise. The collapsing bubbles erode the dust and dirt on the cleaned surface and then liquid flow takes dirt away from surface. For protection foot’s surface from cavitation erosion in the passages, a special plastic coating is used.

Thus the application of cavitation bubble collapse for the cleaning process at the micro level leads to improvement of the robot’s design because of the replacement of a complicated mechanical system that used brushes on the macro level.

2.5. UTILIZATION OF S-FIELD DEVELOPMENT TREND

This technical system evolution trend states that the development of technical system proceeds in the direction of increasing the S-Field involvement [1].

The meaning of this trend is that non S-Field systems strive to become S-Field. In S-field systems, the development moves in the direction of a transition from mechanical to electro-mechanical and then to electro-magnetic fields. Increases in the degree of dispersion of substances, the number of links between the elements and responsiveness of the system are additional benefits of this trend.

Some examples illustrating application of this trend in the solution of problem are presented below.

PROBLEM SOLVING 9. Vacuum wall-climbing robots with pneumatic or vacuum drives as considered above (general view of this robot is shown in fig.1) have a well-known disadvantage: they cannot be autonomous like automobile and so they cannot move for a long distance. Because of pneumatic/vacuum and electrical lines, which connects robot's mobile module with land-based power supply equipment, restricts the distance and mobility of this robot.

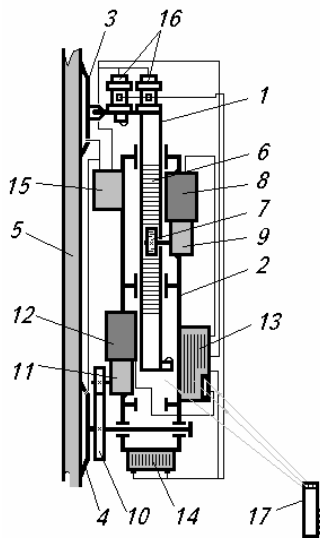


FIG. 23. Scheme of the two-feet climbing robot with electromechanical step-by-step drive [6]

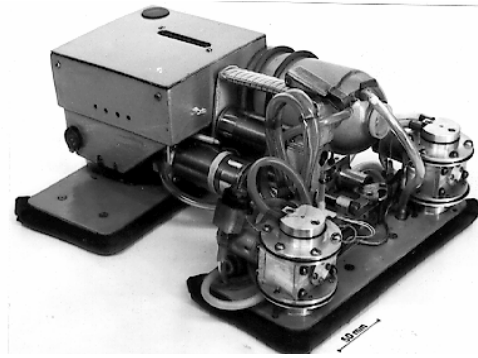


FIG. 24. General view of the two-feet climbing robot

In accordance with the trend of increasing the S-Field involvement, it was proposed to use transition from mechanical (pneumatic/vacuum) drive to electromechanical drive by using electric motors. This transition was very promising and helpful because it gave the possibility to make an autonomous robot module without any connecting lines.

The first electromechanical robot was very similar to the pneumatic robot. It had two vacuum feet 3 and 4 (fig. 23) installed on moving frames 1 and 2. The robot can move in any direction on the arbitrary oriented surface 5. The linear moving of the module is carried out with the aid of the first electrical motor 8 with reducer 9, rack 6 and 7. Rotation of the robot is carried out with the help of gearing 10 with reducer 11 and second electrical motor 12.

The motion principle of this robot is the same as previous pneumatic one. The module can move step-by-step rectilinearly with help of the first motor and can turn to a new direction around one of the feet with the aid of other motor. The robot moves step-by-step and does not detach feet from a surface: by alternating high and low vacuum pressure from one foot to the other, the robot plods along.

The important difference of this design from pneumatic-vacuum designs is independence of the robot from vacuum pipelines and electrical wires. Two vacuum pumps 16 are placed directly on the mobile module and supply negative pressure for robot's feet 3, 4. That would be impossible to do in a robot with a vacuum linear drive. Because in that case, it is necessary to use vacuum pump with large capacity with great mass for power supply of grippers and drive at the same time. Electrical battery 14 also can be placed on the module and supply electrical motors 8, 12 with their drives, mini vacuum pumps 16 and vacuum valve unit 15. Additionally, the robot's control system 13 has been realized without any wires on the basis of the infrared principle with a remote control 17.

Thus a new electromechanical robot's design corresponds to a system of evolution on the S-Field development trend and so the robot has new additional technical properties and advantages.

PROBLEM SOLVING 10. This problem is related to improvement of the robot's motion parameters. Long service tests of previous design have showed that when a robot moves on the vertical surface along a horizontal line its track is not as linear as required. During motion along a horizontal line the robot deviated from this line under its own weight. The problem was caused by the difference in mass distribution between feet. When one foot was being adhered to surface the other foot was being moved from first one. This created a load torque by the mass of the equipment placed on it. Under this load, the elastic part of adhered foot was being deformed. So, the robot slid down and deviated from the horizontal course.

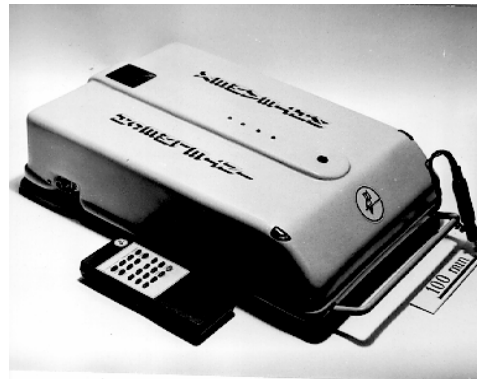
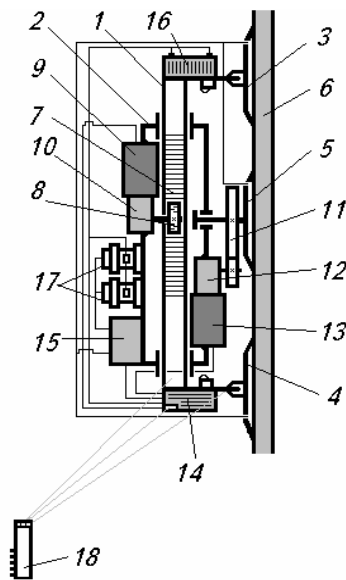


FIG. 25. Scheme of the climbing robot with middle foot and electromechanical step-by-step drive [6]

FIG. 26. General view of the three-feet climbing robot

For solving of this problem for providing of uniform distribution of masses loaded on the robot's feet, it is offered to divide in half one of the feet and put between the other middle foot. In fig. 25 and 26, the scheme and photo of the general view of this robot are shown. The middle foot 5 is fixed on frame 2 and placed between half-foot 3 and half-foot 4 which are mounted rigidly on other sliding frame 1 and connected with one vacuum line. In fact, functionally half-foot 3 and half-foot 4 are one divided foot. Using middle foot 5 between divided foot 3, 4 during motion along the horizontal line leads to balanced distribution of masses relatively robot's centre of mass located on foot 5. Because of a load torque on one half of-foot 4 get balanced by opposite load torque of other half-of foot 3. Relatively, central foot 5 eliminates the robot's deviation from its horizontal course.

The rectilinear motion of the robot is carried out with step-by-step sliding of feet on surface 6. During the motion, the robot can change course by simple rotation around middle foot 5 that is adhered to

working surface 6 by bigger value of negative pressure and foot 3/4 with small negative pressure are rotated for new direction of motion.

Thus by dividing or segmenting one of the vacuum feet gave new property for stable and precise movement of the robot along the horizontal line without deviation on the vertical surface. Just make note that segmentation is increasing in the degree of dispersion of substance and correlates with S-Field development trends.

PROBLEM SOLVING 11. As mentioned above, in S-field systems, the development moves in the direction of responsiveness of the system. The next problem solving is devoted to increasing of the responsiveness of the robot or it's controllability and manoeuvrability.

It is well known that in comparison with other kinds of vehicles, the wheel machines have the best controllability and manoeuvrability. Wheel principle of motion has another important advantage for climbing robots. This advantage is "non-stop movement" which is provides better quality motion for painting, welding and diagnostics than the step-by-step principle of robot's movement with short-term stops. Therefore, during implementation of this project, the wheel vacuum wall-climbing robot design was developed and manufactured.

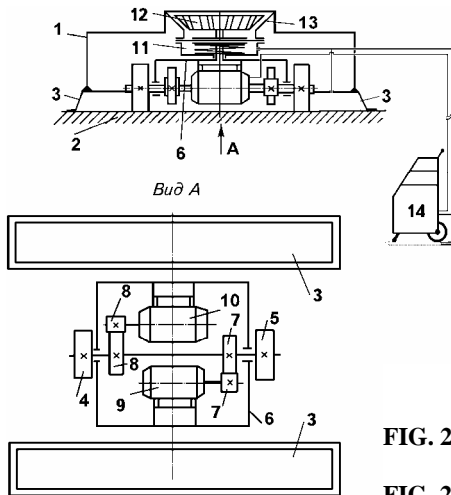


FIG. 27. Scheme of wall-climbing robot with electromechanical non-stop wheel drive [6]
FIG. 28. General view of the wheel wall-climbing robot

In fig. 27 and 28, the scheme of the vacuum wall-climbing robot with non-stop wheel drive and photo of it's general view are shown.

The robot is adhered on a smooth surface with aid of two vacuum feet 3, immobile relatively to body 6, and can move on this arbitrarily oriented surface with the aid of a couple of wheels 4 and 5. The wheels are rotated by two electrical motors 9 and 10 through reducers 7 and 8. The rectilinear motion of the robot is carried out by wheels 4 and 5 and rotated on surface 2. Turn for the new course is realized by rotation of the body 6 with the aid of clutch 11 around its own axis.

Thus, wheel robot has non-stop movement and increased controllability and manoeuvrability. The robot can be used for "dry" work including painting, welding and diagnostics. However, wheel drive cannot force a big load. Under that load, the wheels slip on the working surface and the robot cannot move. Even more so, this robot cannot be used for cleaning on a moist or slippery surface.

PROBLEM SOLVING 12. How to preserve non-stop motion principle with good controllability and manoeuvrability of wheel robot and to remove wheel slipping under load?

Obviously wheels slip on the surface under a load because vacuum feet have bigger sliding friction with surface in comparison with rolling friction of the wheels. It is interesting, we come back to similar technical contradiction which we started this publication!

Technical Contradiction 1: If a big vacuum value is used under vacuum foot then rolling friction force between wheels and surface is increased (good!) but sliding friction between feet and surface is increased as well (bad!)

Technical Contradiction 2: If a small vacuum value is used then sliding friction force between feet and working surface is decreased (good!) but rolling friction force between wheels and surface is decreased too (bad!)

Physical Contradiction: The friction between a foot surface and working surface should be big for stable work of the robot without occasional sliding and should not be big (should be small) in order to robot can easy move.

Ideal Final Result: The vacuum foot itself provides a big friction for elimination of robot's sliding and easy reliable robot's motion (like at low friction).

One of the possible solutions in IFR direction is vacuum foot in the form of a caterpillar. The robot's scheme-design with a caterpillar foot is represented in fig. 29. The photo with robot's general view is shown in fig.30.

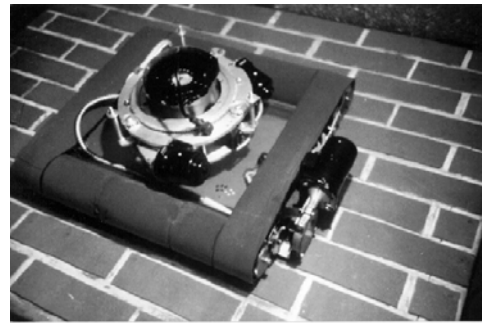
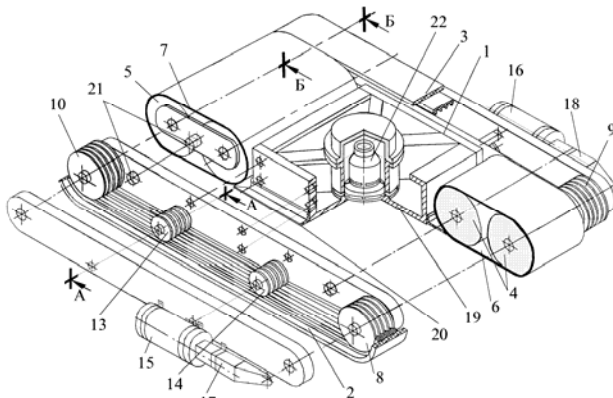


FIG. 29. Scheme of the caterpillar climbing robot with electromechanical drive [16]

FIG. 30. General view of the caterpillar climbing robot

Vacuum caterpillar-foot is designed under body 1 with two side elastic caterpillars 2, 3 and two elastic double-rollers 6 in front and 7 behind. These components make closed vacuum chamber and vacuum is created inside it by highly productive vacuum pump 22. Components 2, 3, 6 and 7 are rotated by independent electrical motors 15 and 16.

The robot can move on a vertical surface by rotation of components 2, 3, 6 and 7 and their friction with the surface on its linear path. The robot's turning during motion is carried out by different speed rotation of motors 15 and 16, and correspond with the elastic side caterpillars 2 and 3.

Thus, in caterpillar robot design, all components of the vacuum foot are with rolling friction without counteraction to motion like in previous wheel design. Increasing the vacuum under the caterpillar-foot leads to improving of the vacuum adhesion with working surface and the elimination of the robot's sliding under a load, for instance. The caterpillar vacuum robot successfully combines reliable vacuum adhesion even on brick surface with non-stop motion principle and good controllability and manoeuvrability of the wheel robot.

7. CONCLUSIONS

Application of different TRIZ tools is considered in this paper through the development of various levels of one technical system: we started from improvement of simple system's component vacuum foot with ARIZ application and finished to designing of new climbing robot constructions with utilization of TRIZ evolution trends.

We notice that considered algorithmic process for problem solving contains only first five parts and ARIZ parts 6-9 have not been published because of time limitation. These last parts, of course, are important too and will be considered during the presentation briefly.

Investigation of some algorithmic steps has been conducted during performed analysis. Application of ARIZ in the different conditions requires considering some reasonable modifications corresponding to the real requirements of the customer. These conditions and requirements are seriously different sometimes and especially, for instance, between a scientific laboratory and a company with mass-production capability. Therefore, it becomes possible to talk about application of different versions of algorithmic logic for different specific situation. We just make the remark that in the present time in TRIZ community different directions of TRIZ already exist: "theoretical"/"educational" and "applied".

TRIZ was born as an empirical science on the base of summarizing of existent experience and knowledge. Therefore authors are sure that further synthesizing obtained experience and knowledge of features in different application, their accumulation and comprehension are important things now as before will lead to improvement of algorithmic logic and increase efficiency of problem solving.

The results of scientific researches and developments on this project have been awarded two national grants from the State Committee of Russian Federation on Higher Education No.3-11/93, Research Program "Vacuum Equipment and Technology" (Russia, 1993) and No.29-35, Research Program "Robotics for Hazardous Environment" (Russia, 1994).

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