Service Robots for Motion and Special Applications on the Vertical Oriented Walls

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Abstract

This chapter is focused on the area of mobile systems of service robots for motion on the vertically oriented glass walls (e.g., facades of high-rise building) with the aim of their using in many inspection and technological applications. Preliminary part clearly maps the basic mechanical principles and approaches to mobile platform design with respect to the concept of kinematic chain and type of actuators. Conclusions of extensive research activities are presented, and on this background, the new design development of mechanics of robot mobile platform was made and uses two parallel placed parallelograms. The control system is based on an industrial computer, includes a module for wireless communication, and is equipped with a laser and an ultrasonic position sensor. Movement members are equipped with individual electric actuators and vacuum gripping system, which consists of smart ejectors in combination with active suction cups. Given that the load character of the suction cups during the robots movement on the vertical wall is very unfavorable, considerable authors' attention has been paid to the analysis of the deformation behavior of suction cups so as to determine the limits of external radial load to the stable contact, and discusses the possibility of increasing the radial load of gripping elements in relation to the contact surfaces character and vacuum levels.

Keywords: service robot, vertical wall, vacuum, servo actuator, special service application, combined vacuum element, suction cup, safety coefficient, numerical simulation

1. Introduction

Construction of high-rise buildings with facades made of protective glass fixed to supporting grids is a contemporary trend in modern architecture. There has been a long-term increase in the demand for devices and new technologies, enabling users to deal effectively with problems concerning cleaning, inspection, installation and other service applications. Inspection of the potential surface disruptions of large pressure vessels is just one of many examples. A number of service robots or, more precisely, mobile platforms with different movement characteristics as well as various abilities to deal with surface height differences have been developed recently.

The existing mobile platforms for motion on vertical glass walls have had either the stepping [1–4], continuous [5, 6] or pseudo-continuous motion [7], and the force of holding on the glass wall has been produced using the active-vacuum suction cups and modules (holding systems using materials with a high degree of adhesion are also currently presented). The stepping motion of the mobile platform is realized by means of rectilinear pneumatic motors or reciprocating linear electric actuators. Vacuum in the leg suction cups is released after platform body is fixed to a wall using the force produced in the active suction cups; then, the legs are pulled away from the contact with the glass wall and repositioned by stepping translational motion.

Furthermore, the legs are pulled back to the glass wall and fixed by vacuum set off in leg suction cups. Body of a mobile platform performs similar cycle of the motion by step. Among most significant disadvantages of this design belong to a complicated design of the electric-actuator transformational unit, a considerable weight of translational motion units and an intermittent motion of the mobile platform.

Approaches based on a design with the pseudo-continuous motion are realized by rotary motion of the stepping unit with a horizontal or parallel movement perpendicularly to the glass wall plane. Continuous systems are based on use of oval suction cups — vacuum chambers located on conveyor elements. Designs using collapsible elements on rotary wheels are quite exceptional. These approaches involve using materials coating with adhesive layer [8].

On the basis of theoretical studies, the first generation of the service-robot mobile platform [9–11] was developed and its operation was successfully tested on a glass wall. Verified design of the motion principle was subsequently optimized and used for the second generation of the mobile platform [12]. The motion was not changed as a matter of principle, but by application of the new frame design and smart servo-actuators. That brought required reduction of weight and effective carrying capacity was increased up to ca 25 kg. Moreover, motion possibilities were extended by a next motional axis, allowing the platform to be rotated around its axis perpendicularly to the contact wall plane. This offers an advantage in compensation of motional deviations from the preselected direction, for changing of the platform direction from vertical to horizontal and so on.

Optimized motion platform with improved load capacity might be used for many technological operations. Currently, two superstructures were realized: one for dry or wet cleaning of the glass facades of high-rise buildings and the other for camera-assisted inspection tasks.

Load capacity is for mobile platforms essential and depends on the mechanical and electrical design of the platform. Therefore, new composite materials and design techniques are used, the platform weight is reduced and load capacity is increased. Exceptional demand has been put on a design of new gripping system based on combined vacuum elements, when materials with a high degree of surface adhesion [13] have been applied. Authors describe this in detail at the end of this chapter.

There is the initial research and first generation of service robots for movement on vertical glass facades described in the second chapter. The third chapter deals with optimized version — second generation of the service robot. Safety aspects of the vacuum suction system are described more in detail in Chapter 4. Chapter 5 introduces possibilities for radial carrying capacity increase. The use of deformation passive suction cups in climbing service robotics is discussed in the last section.

2. Development of the first service robot generation

The service robot mobile has been developing since 2008. During this time period, the platform has gone through several stages of development. The initial stage was represented by a project of the holding mechanical concept, and another one included drives and control design; then, subsequently, a remote communication including a graphical user interface was solved. Several robot versions (**Figure 1**) were designed during the project. They differed especially in maneuverability, that is, possibility to change the robot motional and orientation sequence in dependence on the surrounding environment topology. Patented pseudo-continual stepping motion system was used in all of the versions. This is presented by a cyclic alternative movement of the robot legs and body. The step size is firmly fixed by an interconnecting crank length.

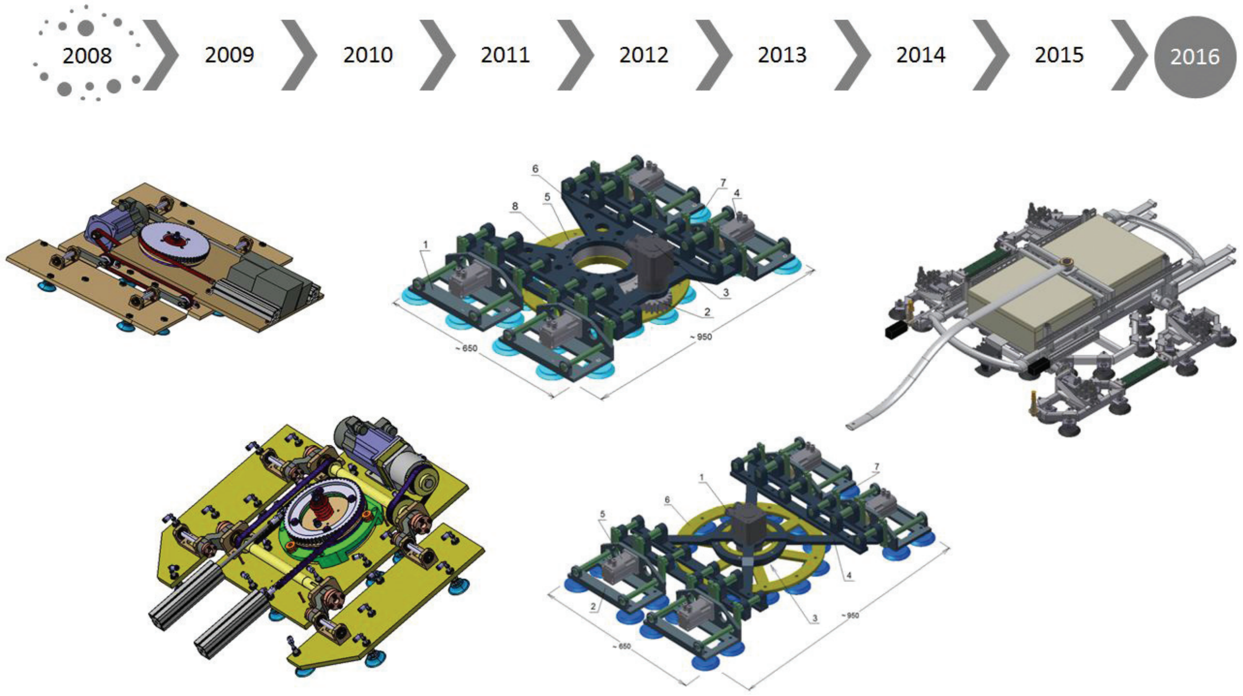

Figure 1. Development of the mobile platform in variants.

The first version of a functional sample of the robot platform (**Figure 2**) was laboratory-tested with very good results. It is a partially autonomous solution with a stepped motion during which the platform legs and body motions take place step by step. A force bond, that is, keeping the platform on the vertical wall, is provided by active suction cups in combination with a system of smart pneumatics. A pneumatic circuit was projected with respect to safety aspects of the motion along vertical walls. An arrangement of 24 suction cups was optimized in view of the model results when the specific load of suction pads and the vacuum interruption during the platform motion over the real construction of the building glass lining were indicated. Suction cups were divided up four sections at six pieces each. Each section is controlled by one smart ejector having the vacuum indication and quick response. Each suction cup is equipped with a self-closing vacuum supply valve if the vacuum space tightness under the suction cup is disrupted.

A drive is formed by a pair of parallelograms, belt gear and three-phase step motor which is controlled by a power unit FM STEPDRIVE directly connected with a control unit based on a program logic control [14, 15]. This concept can be considered to be promising for the cleaning robot application intended, that is, when the robot will use for a building with its skin negative inclination (an inverted pyramid system). In the course of the driving crank rotation, the pair of the platform "feet" and "body" is set in motion alternately and stepping occurs when connecting vacuum into appropriate sections of the suction cups of motional elements. Quick alternations of an under pressure in the vacuum suction cups and their reaeration are provided in the connection with measurements of the crank positions and the vacuum values. The motional sequence control is allowed applying Programmable Logic Controller (PLC).

Main functional units were verified during tests of the first version of the robotic mobile platform. The accent was put on the proper mechanics of the chassis, sensory subsystem and driving system and control. Unequivocal system defects and limits were established after subsequent interpretation of operating data. Based on the obtained experience, demands for the new generation service robot were defined. Situation is clearly visible in **Figure 3**.

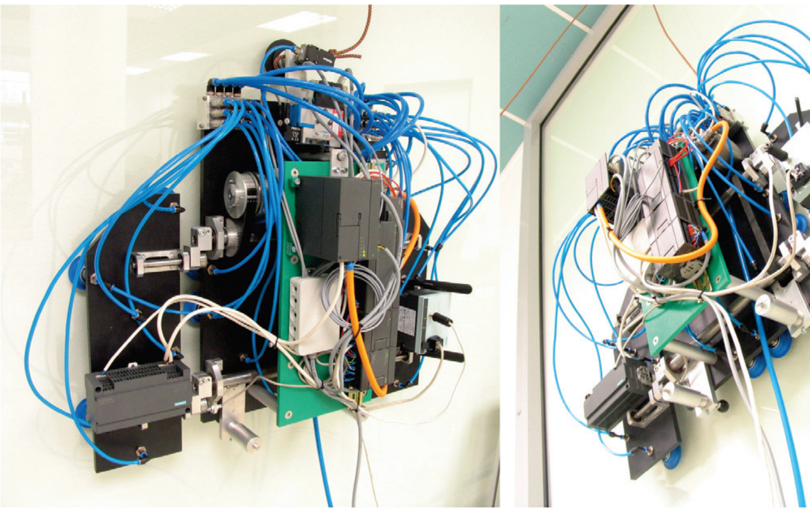

Figure 2. The first generation of the mobile platform.

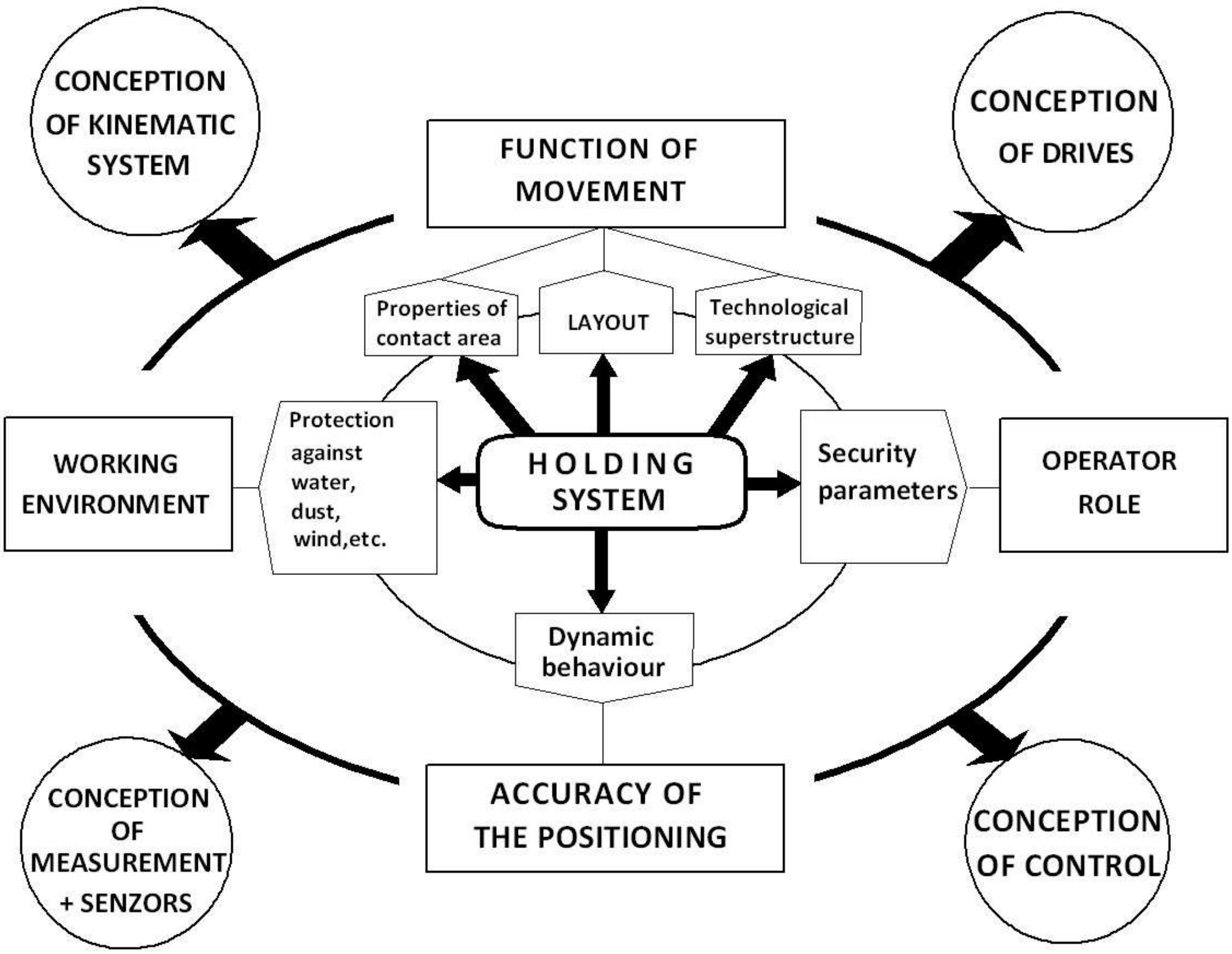

Figure 3. Overview of system links of the mobile platform.

Optimal functioning of the robot is obviously significantly affected by a design of its kinematical chain, drives and holding system. It is appropriately a determining factor for fixing safety parameters; these parameters influence the robot dynamic behavior, layout, contact plane characteristics and eventually staff operation.

3. Second generation of the service robot

Based on the laboratory tests of function sets of the first-generation mobile platform of the robot as well as subsequently found defaults, system connections (relations) and demands for a design of the robot second generation were defined unambiguously with the aim of improving the system (drives) dynamic behavior, maneuverability, safety, control comfort, progress of use properties, effective weight and last but not least also cover design.

The second-generation platform (**Figure 4**) comprises a compact duralumin frame interconnected with a pivoted chassis through a rotary servo drive; by this way, the robot body is created. Moreover, the pivoted chassis is fitted with hinged active suction cups the arrangement of which can be set up due to a character of the contact plane (façade system) geometry. The platform

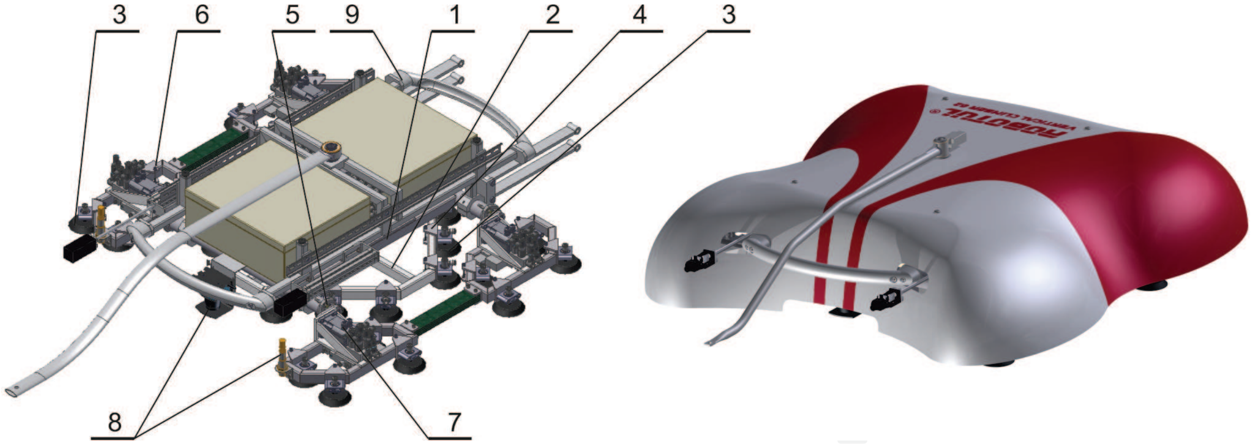

Figure 4. Computer model of the second generation of the mobile platform (*1* — frame, *2* — pivoted chassis, *3* — suction cup, *4* — adjustable holder, *5* — crank, *6* — motional leg, *7* — rotary servo drive, *8* — sensors, *9* — extended frame for superstructures installation).

frame is connected with four legs by means of pivoted cranks. Each leg is fitted with suction cups and an individual electric rotary servo drive [16].

Robotic legs are joined together by a flexible part on both sides of the platform. This flexible part works as a parallelogram in its motional function, and simultaneously, it compensates the leg positional inaccuracies in the contact with a glass wall or, for example, low-profile construction elements of a façade anchoring systems.

The motional sequence is realized as follows: under pressure is brought into the suction cups, and the pivoted body is fixed on the vertical wall. During the initial fixation, leg cranks are quarter-turned normally to the contact surface. This allows turning the platform frame to a required direction. Subsequently, the legs are turned back by ca. 90° and fixed on the wall by bringing a vacuum in leg suction cups.

The vacuum under the body suction cups was cancelled in the second phase. The cranks are turned by 180° with legs fixed on the wall; thus, the body of the service robot is moved one step forward. Continual forward or backward motion is realized by alternating motion of the platform body and legs, and cranks are always rotated by ca. 180°. Appropriate pressure characteristics are synchronized with the movement. To achieve the desired operating safety, suction cup system was divided into several independent sections with the local source of vacuum; contemporary ejectors with integrated sensors of vacuum and a blowing pulse function were used.

For safety reasons, an extension frame was designed, allowing a pivoted suspension arm, power chains and the robot composite cover to be attached (**Figure 5**). Construction elements for fixing technological extensions and operating grab handles are parts of the frame. In **Figure 6** is illustrated the service robot final solution with a dock station, allowing the system to be provided with a user Human Machine Interface (HMI), contact panel making remote control, standby battery supply, computer and so on. From the standpoint of the robot control, a user program was created based on the platform of the programming language ANSI C, respectively C++, with a support of software tool Automation Studio from the B&R Company. The program is divided up into several independent logic structures for which partial function

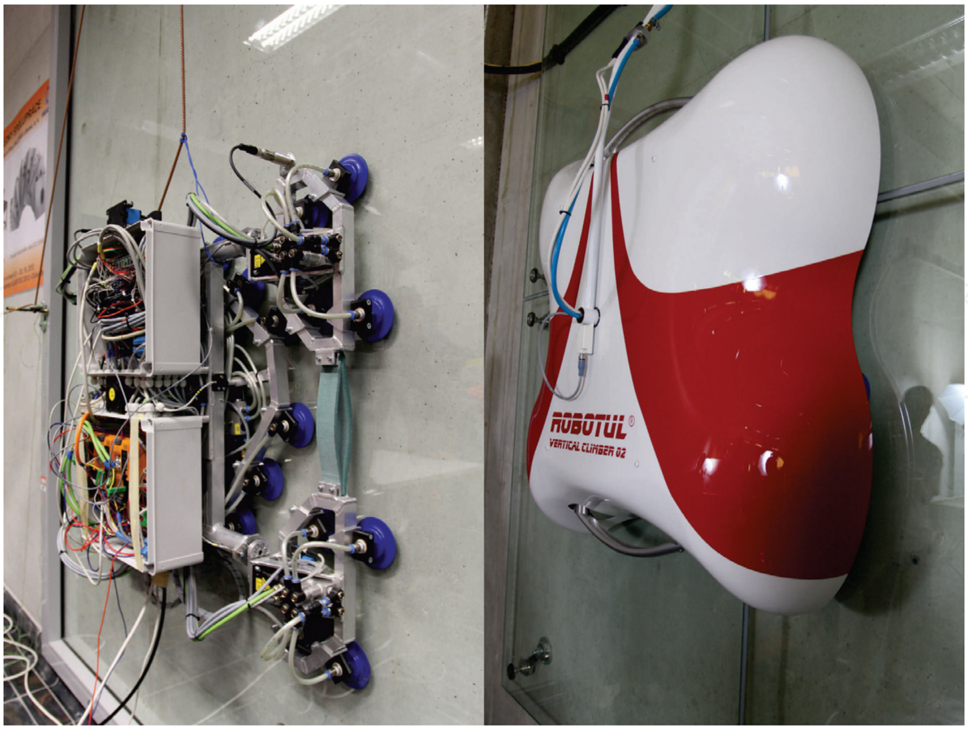

Figure 5. The mobile platform without and with the composite cover.

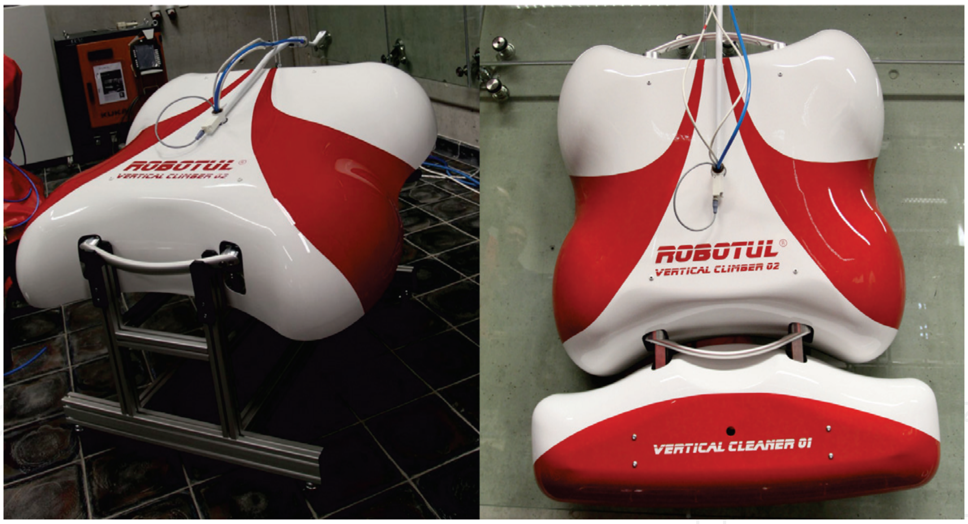

Figure 6. Service robot with a dock station and cleaning unit.

blocks were created, making a communication of the industrial PC with digital servo amplifiers of the rotary drives possible.

In view of the carrying capacity, respectively, the platform weight minimization, the frame (**Figure 4**, pos. 1) strength was analyzed [17]. Based on this analysis, a minimum thickness of the frame bearing profiles wall and connecting plate was predicted, considering tilting moment 40 Nm in the presumptive mass center distance 100 mm and the total weight of 41 kg. Results from the computer simulation propose a weldment arrangement (**Figures 7** and **8**).

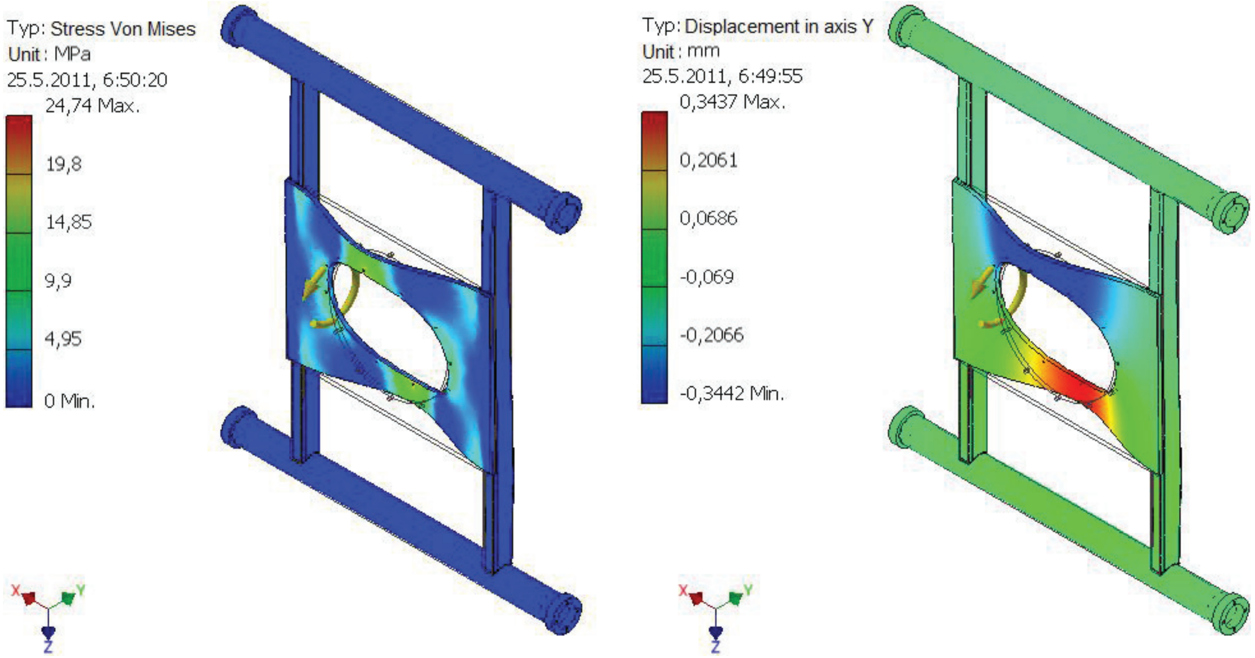

Figure 7. Stress and deformation fields in the frame without ribs having the connecting plate of 6 mm thickness.

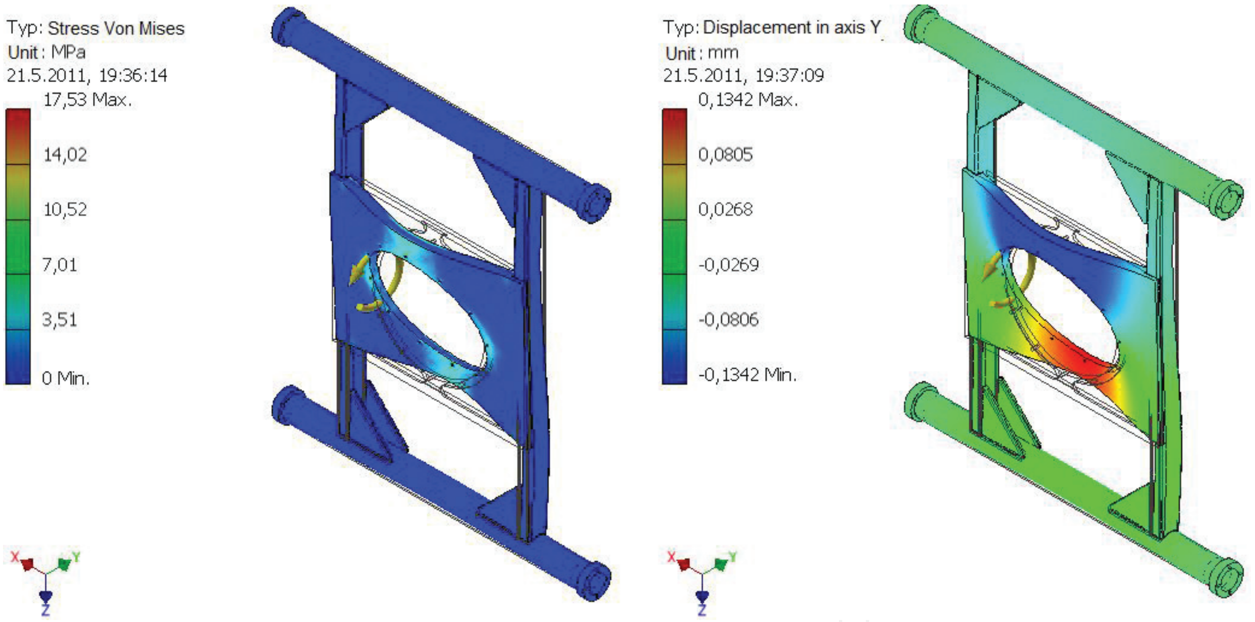

Figure 8. Stress and deformation fields in the optimized frame.

Stress and deformation fields in the frame were analyzed based on the obtained data. It allowed adapting the initially proposed solution by the use of additional reinforcing ribs. These were placed inside the frame, and further, they will be used for placing other accessories of the mobile platform in common with a free space outside the frame. The thickness of the plate was increased from 6 to 15 mm in the place of ribs to reach higher rigidity. It also reduced stress in the optimized frame by 29% — 17.53 MPa in comparison with the initial design. The maximum deformation was reduced by ca 60% — 0.134 mm.

4. Safety aspects of vacuum holding system of robot

Authors' considerable attention was directed to problems being connected with designing a vacuum gripping system influencing decisively the robot stability and safety holding on vertically oriented walls. For that purpose a computer analysis of deformation behavior of the individual suction cup under dominant loading in the radial direction was created. On the base of obtained results a stability limit was defined step by step for which a proportion between an absorbed elastic energy U_{el} and energy of adhesion U_{ad} is very important from the mathematical standpoint [18, 19]. If we proceed from the assumption that

$$U_{el} = E\lambda h^2 \text{ and } U_{ad} = -\Delta\gamma\lambda^2, \tag{1}$$

then it is true

$$\theta = \frac{U_{el}}{U_{ad}} \approx \frac{Eh^2}{\Delta\gamma\lambda}, \tag{2}$$

where E is modulus of contact elastomer elasticity, λ is width of contact body, h is roughness and $\Delta\gamma$ is change in free energy per unit area in which the elastomer is in the contact with the body (surface roughness are filled with elastomer).

If $\theta << 1$, that is an ideal contact when contact surfaces of bodies copy each other perfectly. If it is true that $\theta >> 1$, then the contact is only between maxima of the surface unevenness.

Alternatively to the contact analytical description, a numerical model of the suction cup and the glass contact surface was made up so that the real behavior of elastomer was replaced by the Mooney-Rivlin rheological model [20, 21], and appropriate material constants were computed from the relation (for only uniaxial tension)

$$F = 2A_0 \cdot \left(1 - \frac{1}{\lambda_1^3}\right) \cdot (\lambda_1 c_{10} + c_{01}), \tag{3}$$

where F is tension force, A_0 is an initial cross-sectional area of the test sample, λ_1 is a deformation and c_{10} and c_{01} are Mooney-Rivlin material constants.

On the basis of the calculation using the finite-element method, three principal limit states can be defined (**Figure 9**) for the selected type of the active suction cup of the holding system which correspond to the suction cup contact profile depending on the level of external radial force according to the force analysis carried out in detail in Ref. [22].

If equilibrium conditions of an interaction between the suction cup and contact surface are analyzed in detail [23], then it is obviously true that

$$T + \Delta T_P - F_{RAD} = 0, \tag{4}$$

$$F_U - F_B - F_{AX} - \Delta F = 0. \tag{5}$$

Along the suction cup axis, external axial forces F_{AX} and F_G are acting induced by the under pressure applying on the suction cup active surface. As a result of the suction cup thrust, a

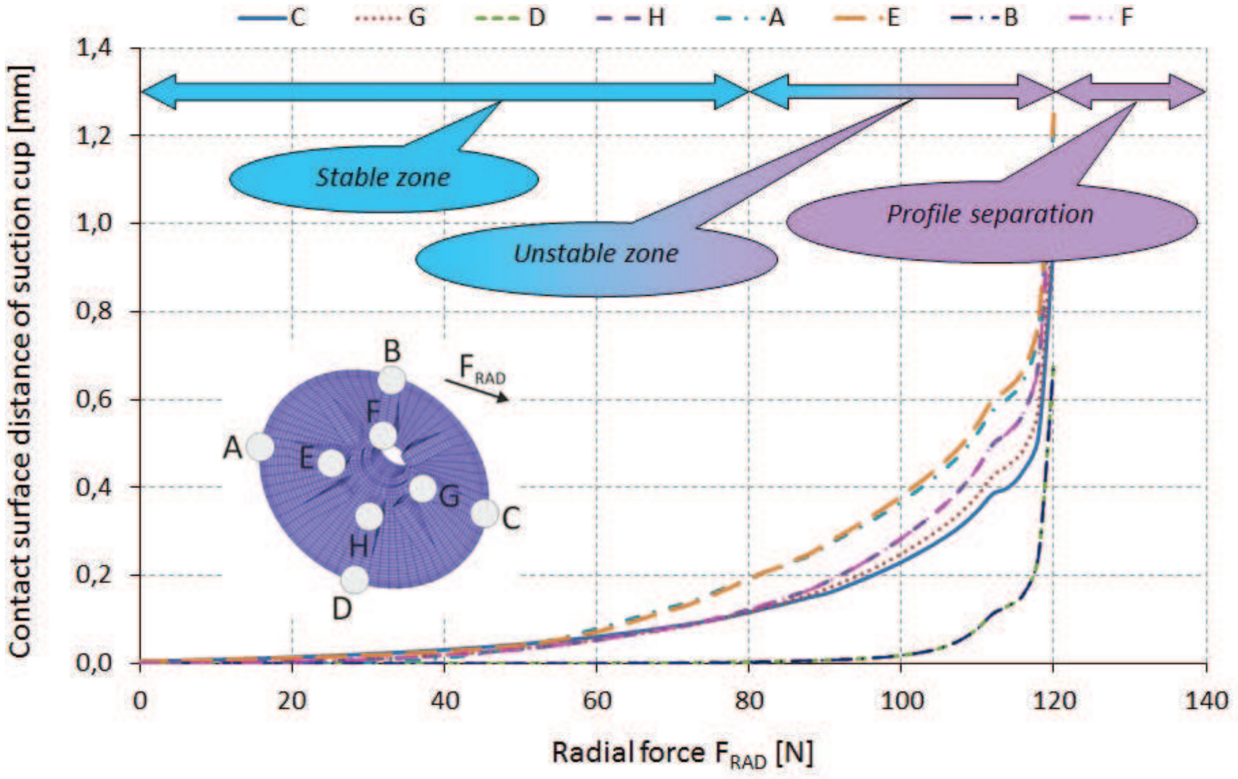

Figure 9. Typical progression of suction cup deformation in the radial direction.

force F_B is acting further, and between the suction cup bottom and the contact wall, an additional force ΔF is making evident. Then, a radial force F_{RAD} at the plane of gripping and a displacing force T on the edge sealing surface are acting. Owing to a friction on the suction cup bottom caused by the thrust normal force ΔF, it is possible to define an additional friction force $\Delta T_p = \Delta F.\ \mu$ (μ is friction coefficient). A theoretical gripping force F_{Gtheor} can be defined for the state of limit equilibrium, that is, when the force ΔF will equal zero.

$$F_{Gtheor} = \frac{F_{RAD}}{\mu} + F_{AX} + F_B. \tag{6}$$

It is not easy to determine the force F_B, and particular calculations were necessary to base on the data found experimentally. If material properties of the suction cup as well as boundary conditions are known, it is possible to use the rule of thumb using the finite-element method. In many cases, the presumption is that $F_B << F_{AX}$ and it can be ignored. As for the real gripping force F_G, the relation is generally true (only for centric holding)

$$F_G = k' \cdot \frac{F_{RAD}}{\mu} + k'' \cdot F_{AX}, \tag{7}$$

where k' (safety against sliding) and k'' (safety against breakoff) are appropriate safety factors corresponding to the direction of the suction cup greatest load for which it is true that $k' > k''$. Usual factor values are $k'' = 6$–8 and $k'' = 4$–5.

5. Possibilities for an increase of the suction cup radial carrying capacity

With the aim of decreasing the robot demands of energy, a new concept was solved relevant to a so-called combined gripping element inducing gripping force by means of vacuum and adhesion. The presumption was that higher level of a possible safety load along the radial direction, that is, along the contact plane, would be reached, and at the same time, the consumption of pressure air would be decreased or kept at least.

The principle of such solution [24] is represented in **Figure 10**. It lies in that: when the gripping element *1* comes into contact with the object handled *7*, the created space *10*, *11* being sealed with the sealing rim *2* is evacuated through the hole *8*; at the same time, the bearing plate *4* is moved optimally into contact with the object *7* by means of the piston *3* which is connected with the bearing plate *4,* and simultaneously, it sealed the space *10*. Part and parcel of the bearing plate *4* is the adhesive layer *5,* forming the contact interface *12* with the object *7*. A thrust level between the plate *4*, respectively layer *5*, and the object *7* is possible to control by the value of pressure in the regulative space *9* above the piston *3* so that the ideal level of thrust can be reached, based on the rim *2* deformation, mechanical properties as well as a surface profile of the object *7*. In this way, it is possible to provide maximal growth of friction forces during holding.

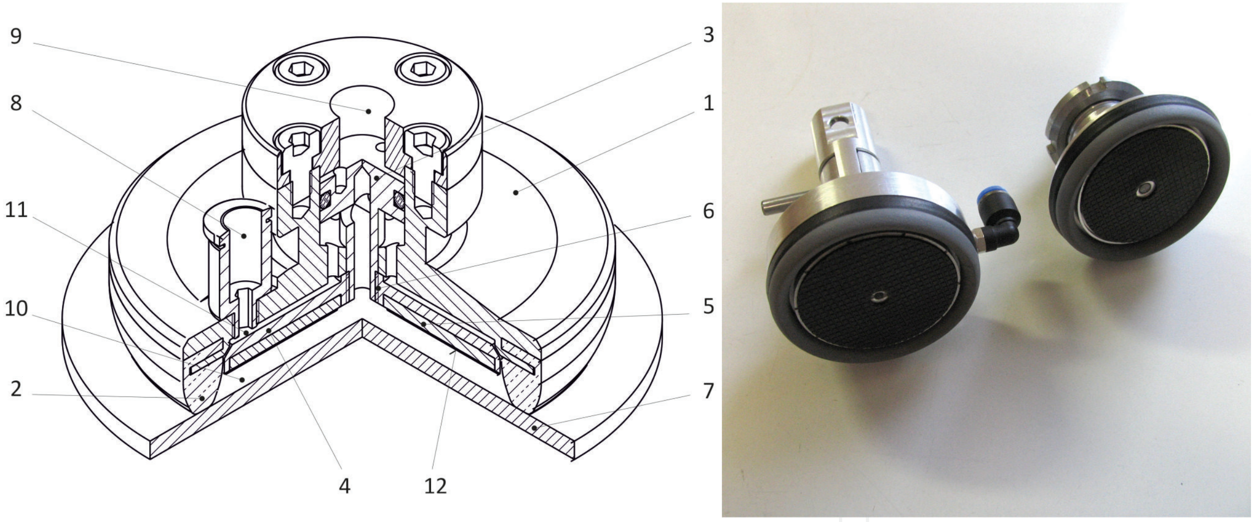

Figure 10. Combined vacuum gripping element.

6. The use of deformation passive suction cup in a holding system

An optimized and simultaneously original solution of the holding system is a possibility to use only deformation, so-called passive suction cups. This solution would allow the service robot to be operated without necessity to use an active source of vacuum dependent on pressure air [25]. Based on equilibrium of forces, a gripping force can be determined provided that the suction cup diameter is not changed according to the relation

$$F_G = \varsigma \cdot F_{Gtheor} = \frac{\pi \cdot d^2}{4} \cdot (1 - K) \cdot p_a \cdot \varsigma, \tag{8}$$

where ζ is a correction to the suction cup rigidity that is introduced due to the real situation where in the moment of pressing the suction cups into contact are in a closed volume pressure less than atmospheric pa. ζ acquires values in the interval from 0.6 to 0.8, and K is a volume ratio which lies in the interval from 0.2 to 0.5 for typical suction cups.

When applying in real conditions, it is necessary to realize that the gripping force values are influenced by the surface quality, material properties of the suction cup, as well as they depend on the holding time, which is connected with leakages of the closed volume between the suction cup and object. For this reason, it is necessary to choose relatively high values of the safety factor $k = 4$–6.

A suitable option for using passive suction cups shows a solution when the suction cup will be deformed actively, so that the under-pressure level can be regulated on the one hand, and leakage losses can be possibly compensated for further growth of deformation on the other hand.

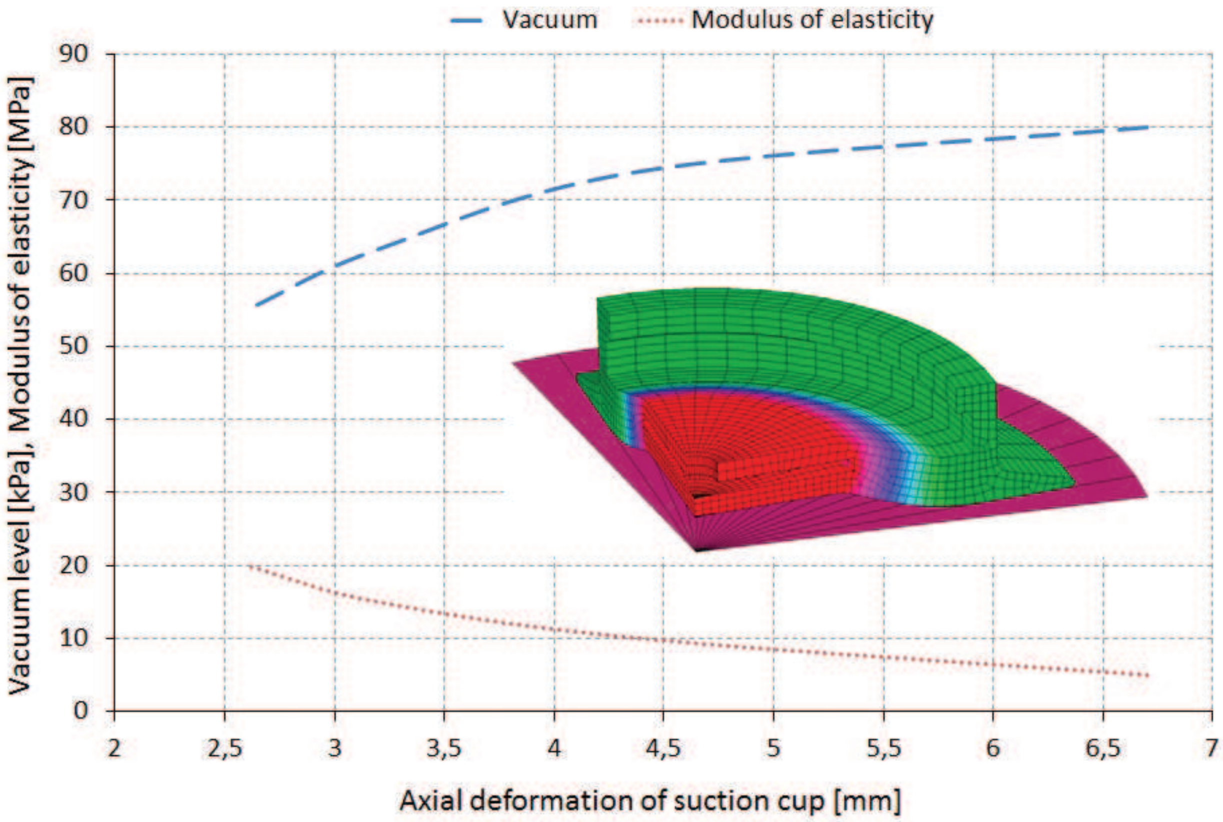

Figure 11. Axial deformation of passive suction cup.

However, there is one great problem, namely that depending on material, geometrical properties of the suction cup and a vacuum final value, this solution needs applying a relatively considerable active force which will induce an appropriate deformation.

The diagram in **Figure 11** shows a course of the suction cup deformation depending on the obtained values of vacuum as well as the suction cup material properties given by a modulus of elasticity E at axis loading with the active force $F_A = 100$ N. It is evident from the given diagram that for $E = 10$ MPa ($c_{01} = 0.3$ MPa, $c_{10} = 1.3$ MPa) the available theoretical level of vacuum is *ca.* 70 kPa. It is necessary to realize that due to a great number of suction cups creating the robot holding system, the given solution is not realizable without a specific technical solution of the mechanical transforming block of the suction cup because the final force load of an additional drive, allowing the suction cups to be controlled directly, will be too high.

7. Conclusion

Basic mechanical systems of the service robots were described, and **concrete solution of the robot mobile platform was presented** in this chapter. The platform allows realizing a motion on vertically oriented smooth-surfaced walls. This solution allows special technological and inspection extents to be installed with a view to realizing, for example, cleaning, assembling and detecting processes. Moreover, a methodology solving deformation contact tasks was managed inclusive of introducing specific boundary conditions being connected with the pressure definition on the contact interface. Also, a deformation analysis of the radially loaded suction cup of the robot holding system was carried out.

Further problems of **defining theoretical and real gripping force of the individual suction cup during axial as well as radial loading were discussed**, and adequate safety factors corresponding to a character of load and operational conditions were determined.

A combined vacuum gripping element inducing gripping force on the principle of vacuum and adhesion **was presented,** having an evident influence on the contact stability. Based on laboratory tests, it was shown that it increases the radial carrying capacity against the system without any adhesion layer by a few 10%.

In conclusion, a **possibility to use only deformation suction cups** in holding systems of mobile robots was analyzed as an alternative to the standard-chosen solution with active suction cups with the aim of eliminating the source of pressure air and vacuum circuit of the mobile platform.

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