## GECKO ROBOT – FINAL REPORT

## 1. STATE OF THE ART

## 2. ACHIEVED AIMS

The scope of the current project was the design, manufacture and development of an autonomous platform for Non-Destructive Testing (NDT) and inspection of wind turbine blades. There were many challenges to be met and the whole project was complicated therefore the development process was long and involved various re-design loops. The most important design considerations, which had to be met, were:

1) The ability of the robot to work autonomously for an extended period of time (at least for the time needed for a complete NDT of a single blade.
2) The ability of the robot to complete the whole testing session within reasonable time, in order to perform a complete rotor test in a working day time.
3) The ability of the robot to carry various types of NDT sensors, which can also be developed and exchanged in the future.
4) The creation of a stable and secure platform without any hazard possibility for the personnel or the turbine structure.
5) The increased movement versatility of the robot in order to enable complex motion patterns.
6) Lightweight solution which could possibly work even at wind turbines not equipped with mechanical lifting winches.
7) The ability of the robot to move on strongly curved surfaces (positively or negatively curved) and perform NDT inspection.
8) The ability of the robot to reach the blade’s leading and trailing edge close enough in order to inspect them.
9) Maximum possible coverage of the blade surface.
10) Implementation of a positioning system in order to enable the position monitoring during the inspection process.
11) Low cost solution which can lead to an affordable product.
12) Creation of an image ‘collage’ which will produce a visual high resolution database of each blade. This database can be analyzed in-situ in order to arrange the needed repair operations, or alternatively it can be stored and further analyzed in a future time.

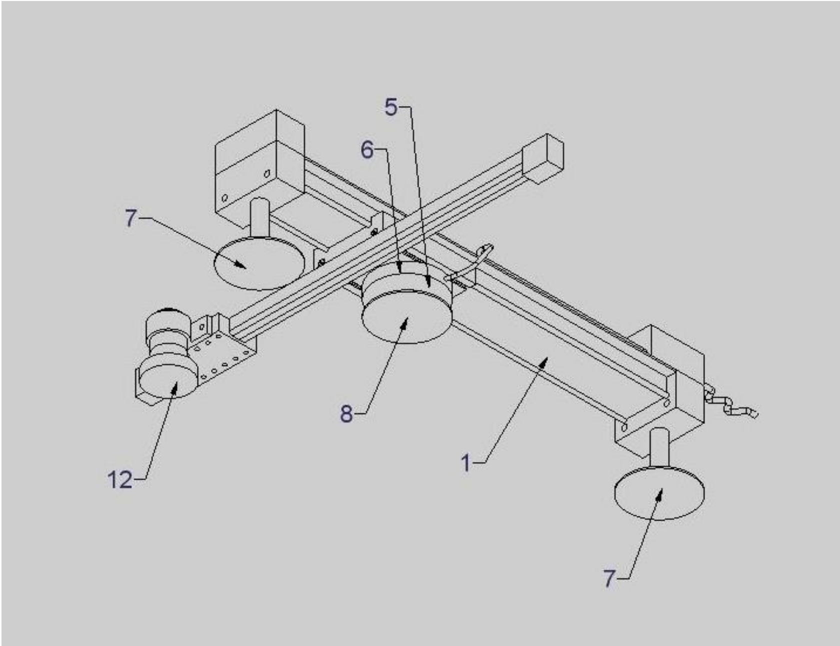


Figure 2. 1: The initial concept of the robotic platform for wind turbine blade inspection consisted of a very simple robotic solution. (Source: Idaswind GmbH photo archive)

In the following chapters the reader can find the detailed description of the design solutions, which were developed in order to enable the robot to meet all the aforementioned key-points, as well as the development process of each of these solutions. These development steps represent **Work Packages (AP) 1, 2, 3** and **4**.

## 2.1 Robotic Platform Development (Version 1 & Version 1.1)

Definitely the power supply was one of the most important considerations therefore the whole design process of the system was strongly influenced by the available power supply systems and their physical characteristics.

*Electric step-motor solution*

The initial design followed the standard solutions of the majority of the existing robotic systems, where the motion is performed by electric step-motors. These motors offer an attractive option since they are relatively compact and powerful; they have precise (on-board) angle measuring system and almost infinite intermediate stopping positions between two extreme positions. Additionally it is really easy to use a toothed belt or gears in order to define the rotational speed of the rotating parts, and in the same fashion to use linear gears in order to translate the rotational motion of the motors to linear motion.

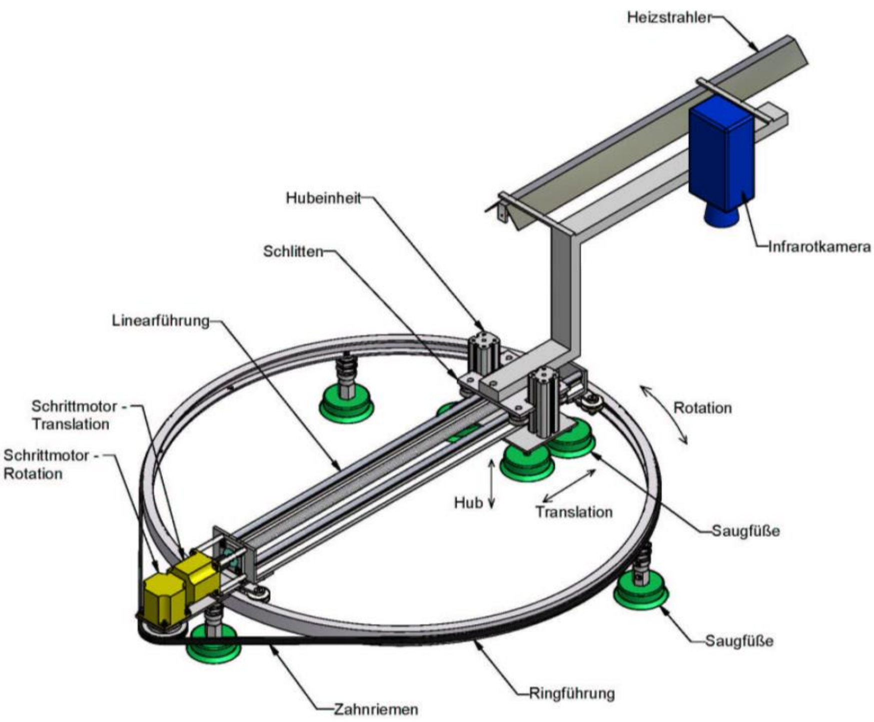


Figure 2. 2: Computer generated 3D model of the initial version of the robot, equipped with turning step motors for the angular and linear motion. (Source: Idaswind GmbH photo archive)

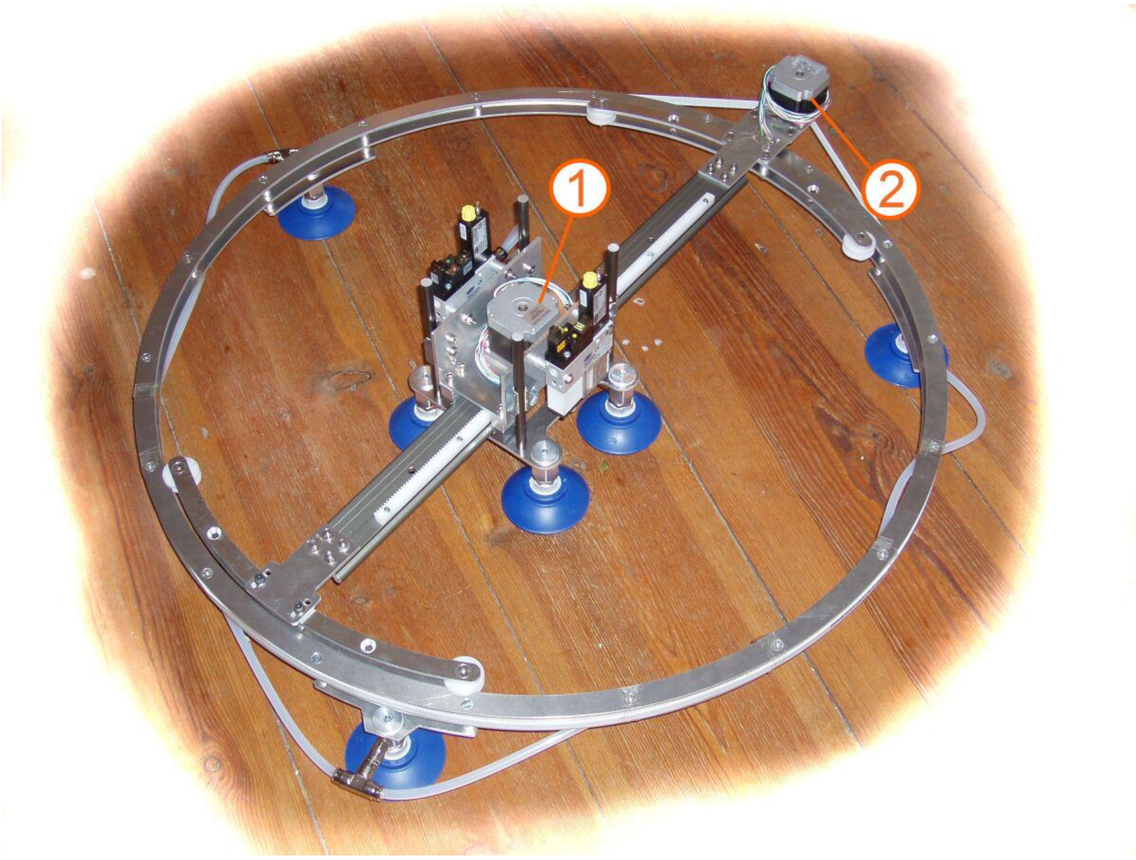


Figure 2. 3: Realized prototype, equipped with step motors for the linear motion (1) and for the angular motion (2). (Source: Idaswind GmbH photo archive)

However the solution of the electric step-motors prototype underperformed during the test phase of the initial prototype, mostly due to lack of power for the motion of the robot on the vertical plane of a wind turbine blade. Since the weight could not be further reduced, new more powerful but heavier step-motors should be installed. However this would be a never ending process leading to a vicious circle since the additional weight of the electric motors is proportional to their torque. It was therefore apparent that a completely new design should be developed.

The adhesion of the robotic structure to the rotor blade surface was performed with elastic vacuum cups supplied by the company Schmalz. The vacuum was produced from a Venturi type air driven pump and was transferred with flexible tubes to the suction cups. The suction cup design was carefully selected from a variety of available designs and offered good adhesion and low weight. When the robot was properly attached to a fine smooth surface, the vertical force of detachment was higher than 300N, ensuring a safety factor of 2.1 against detachment. Consequently the robot could properly support its own weight provided that the vacuum cups could have proper contact with the blade surface.

*Pneumatic drive solution*

The next step on the developing process of the motion system of the robot was the ‘air driven’ concept. All the electric motors were replaced by pneumatic cylinders, which would perform the linear, rotational and vertical motion of the robot. These pneumatic cylinders were selected from the wide range of available cylinders offered by the company FESTO. They offered significant improvements compared to the previous design, mostly due to their robustness and very high force-to-weight ratio. Now the climbing and moving loads and weights could in no way challenge the motion system. It is noted that the largest pneumatic cylinder of the robot, which was used for the linear motion and had an external diameter of 20 mm and could apply a force of 300N, more than two times the weight of the whole robot thus ensuring high agility and significant loading ability.

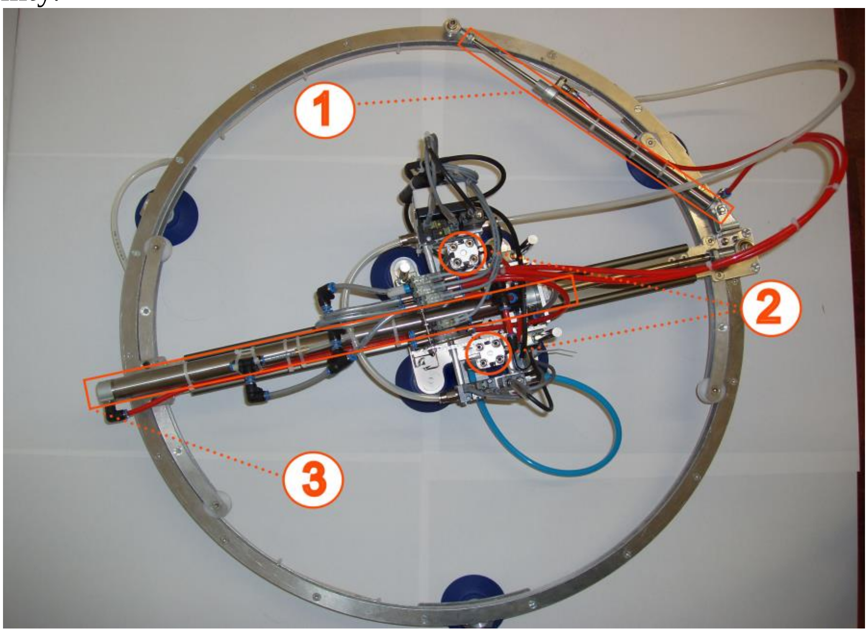


Figure 2. 4: Improved version of the initial prototype equipped with pneumatic cylinders, which perform the angular rotation (1), the vertical elevation (2) and the linear motion (3).

(Source: Idaswind GmbH photo archive)

Of course this design had also some problematic points mostly due to the nature of the pneumatic drive units. A crucial design issue was the transformation of the linear motion of the pneumatic cylinders to a rotational motion, in order to allow the robot to turn. Due to this special demand, a whole new base-frame was developed and the 'ring shaped structure' was introduced. Now the robot was separated in 2 main assemblies, the 'ring shaped outer unit', which would perform the angular rotation and the 'linear inner unit', which would perform the linear motion.

*The mechanical platform*

The ring structure consisted of 2 concentric rings from AlMg alloy screwed together with special screws and spacers. This structure resembled a circular *H-shaped* rod and provided very high stiffness and stability to the outer (ring shaped) unit. The ring shaped unit was equipped with three vacuum cups fixed with high strength aluminum legs. These vacuum cups were connected to the vacuum pumps with a flexible tube.

The inner unit consisted of a base mounting-frame structure, which supported all the electronic and vacuum devices. This frame was equipped with special linear sliding bearings (by IGUS GmbH, which enabled the linear motion of the frame on a special sliding rail. This rail was made of low friction coated aluminum and it enabled the sliding action of the base frame in order to perform the linear motion. The two ends of the sliding rail were mounted on special T-shaped plates which enabled the rotating connection of the 2 main units (inner linear unit and outer ring unit). Additionally the base frame hosted four vacuum cups mounted together in a vertically movable sub-frame and actuated by 2 hydraulic cylinders. This enabled the vertical motion of the robot and therefore the stepping action, which will be explained in detail later.

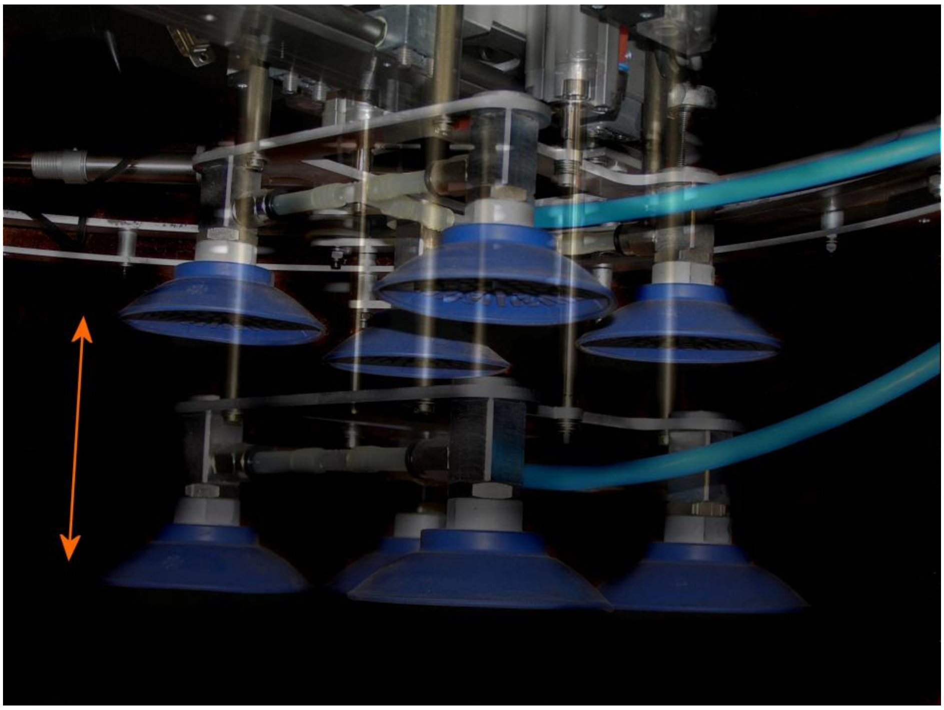

Figure 2. 5: The processed image shows the vertical movement of the vacuum cups of the main sliding unit. (Source: Idaswind GmbH photo archive)

The connection of the two main units was realized by lightweight plastic (POM) pulleys, which were rolling on the outer surface of the ring. The pulleys were equipped with low friction sliding bushings and low friction coated aluminum shafts, therefore the total turning friction of the turning system was very low. The turning action itself was performed by a pneumatic cylinder which was connected to the ring and the inner rotating unit. Both sides of the pneumatic cylinder were rigidly connected to the rotating units (ring and inner unit) and the linear expansion and contraction of the cylinder was translated to a rotational motion of the units. Of course due to the fixed mounting points and the defined length of the cylinder’s moving part, the rotational angle of the units was limited to approx. 50° of rotation.

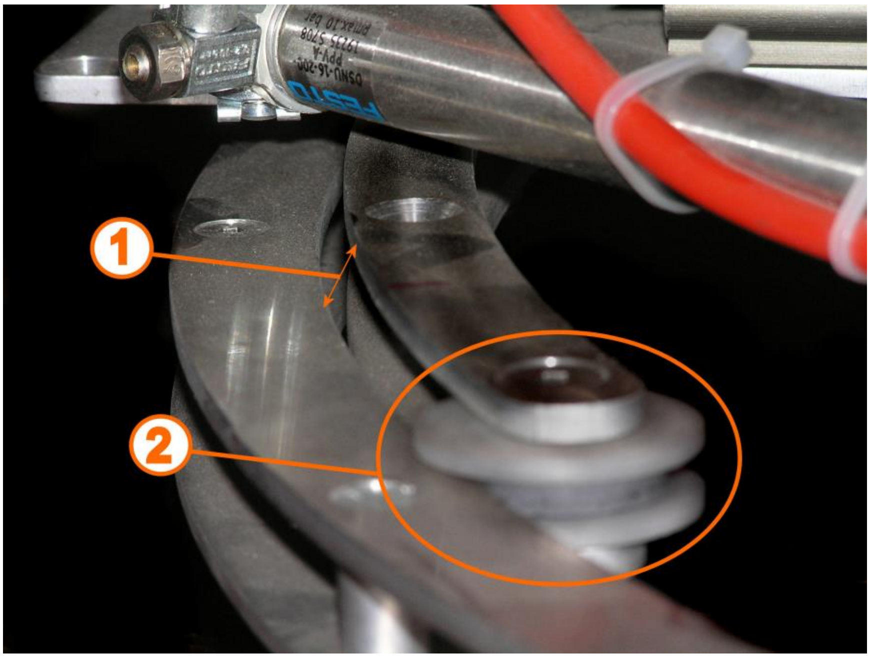


Figure 2. 6: The plastic (POM) roller (2) enables the rolling angular motion of the ring shaped frame and the inner linear unit (1). (Source: Idaswind GmbH photo archive)

*The motion and control*

The linear, as well as the rotational motion pattern of the robot was characterized by incremental movements. In order to move in a straight line, the robot turned the linear slider to the desired direction of motion and then, while being attached to the blade surface with the outer vacuum cups, it lifted the inner vacuum cups and moved the base frame forward (by sliding on the sliding rail). Then the inner vacuum cups were lowered and attached to the blade surface while the outer vacuum cups were lifted in the air. The ring was now moving forward and then lowered once more back at the blade surface. This incremental procedure would be repeated for as long as the forward motion was desired. The rotational motion was generally based on the same concept with the only difference that instead of sliding the base frame, the control system would order the rotational cylinder to expand, turning the robot approx. 50° and then step down again. The next step of commands would contract again the cylinder while the outer cups would be in the air and repeat the process once more. Therefore the robot could perform almost a complete rotation in 7 steps.

In order to control the robot and to enable an autonomous motion it is necessary to implement some kind of stepping sensor method in order to verify the contact of the vacuum caps with the blade surface. This step sensoring process is essential in order to be sure that one unit of vacuum cups (inner or outer) is securely attached to the blade before eliminating the vacuum of the other vacuum cup unit and perform a step. The simplest way of performing the step sensor process is to continuously monitor the negative pressure (vacuum) development at the vacuum system, and to identify the possible stepping situations. Therefore the controller is measuring the pressure of the two different vacuum units and the rate of vacuum reduction. According to pre-defined thresholds the control unit identifies the stepping position and decides if the cups are actually attached on the surface, if they are stepping at some sort of minor cracks or if they are out of the blade's surface (or stepping on big cracks). Consequently if the stepping situation is such that the vacuum cup units can achieve sufficient adhesion then the robot completes the step. Otherwise the control orders the robot to move one step back and take a turn in order to avoid the current obstacle.

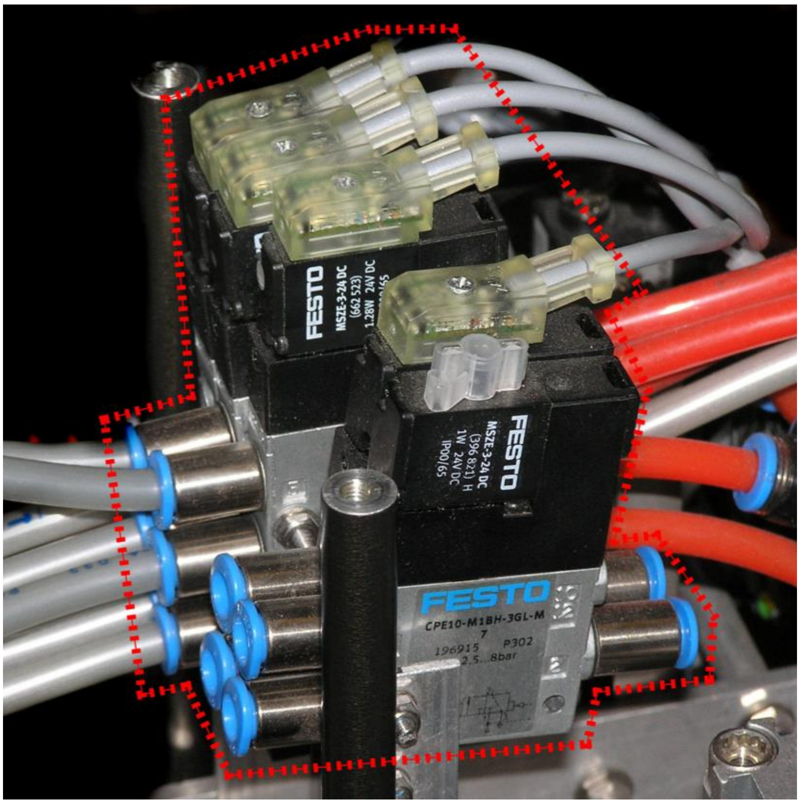


Figure 2. 7: The motion control of the robot was performed by autonomous computer activated FESTO valves. (Source: Idaswind GmbH photo archive)

## 2.2 Robotic Platform Testing (Version 1.1)

After the conclusion of the development process of the Version 1.1 of the robot, an intense testing period was initiated. The robot was tested on vertical surfaces for detachment tests as well as for climbing speed on vertical surfaces. The next series of tests were performed at the laboratory facilities of the Fraunhofer WKI institute at Braunschweig. There, the robot was attached to a 10m part of an old rotor blade in order to investigate the behavior of the robot at 'real life conditions'.

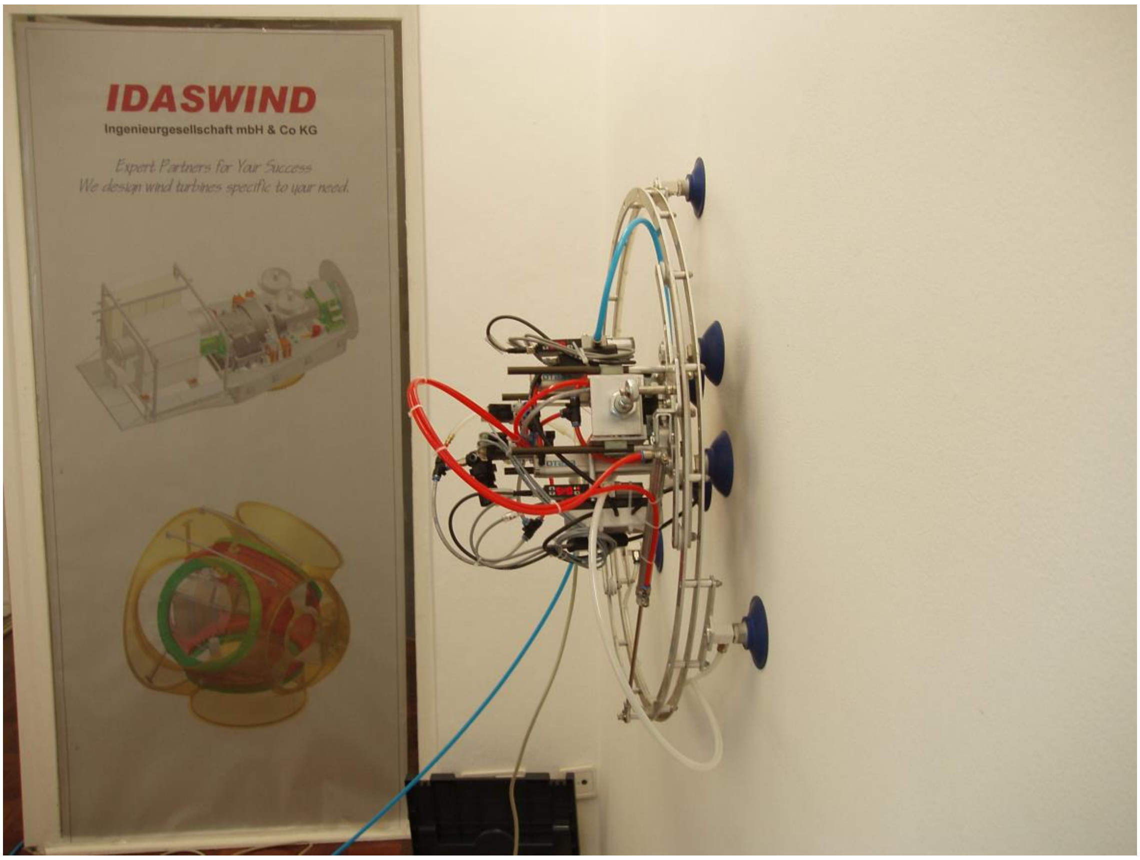


Figure 2. 8: Motion tests on a vertical wall of the lab facilities of Idaswind GmbH. (Source: Idaswind GmbH photo archive)

The test blade was an excellent way to test many different design aspects of the robot in a single test session. The 1st issue for further investigation was the attachment ability of the robot on a real wind turbine blade surface. Initially the robot was attached at a smooth and relatively clean and straight part of the blade and had no problem to achieve perfect attachment to the blade surface. However the next steps of the attachment test were performed in other sections of the test blade where the surface was slightly damaged, cracked or even completely delaminated. The results revealed a totally new path for the future development.

The surface quality problem did not only cause insecure attachment situations during the testing period, but also increased the vacuum consumption, hence the compressed air consumption (since the vacuum pumps are air driven). This issue revealed the limitations of the small (5 Liter) compressed air tank and the 12V compact air compressor. Another important issue that came up during the test session was the performance of the passive step sensoring system. As it is described above, this system uses the measurement of the vacuum level of the cups to estimate if the robot is stepping on the blade or not. However during the motion tests, when the robot was stepping on a big crack and it could not achieve sufficient vacuum, the control system would take that incident as ‘no step’ and would sent the robot one step back. Of course this is not a severe problem as long as it protects the robot from detaching, but when the blade was generally scratched the robot was not able to move forward anymore.

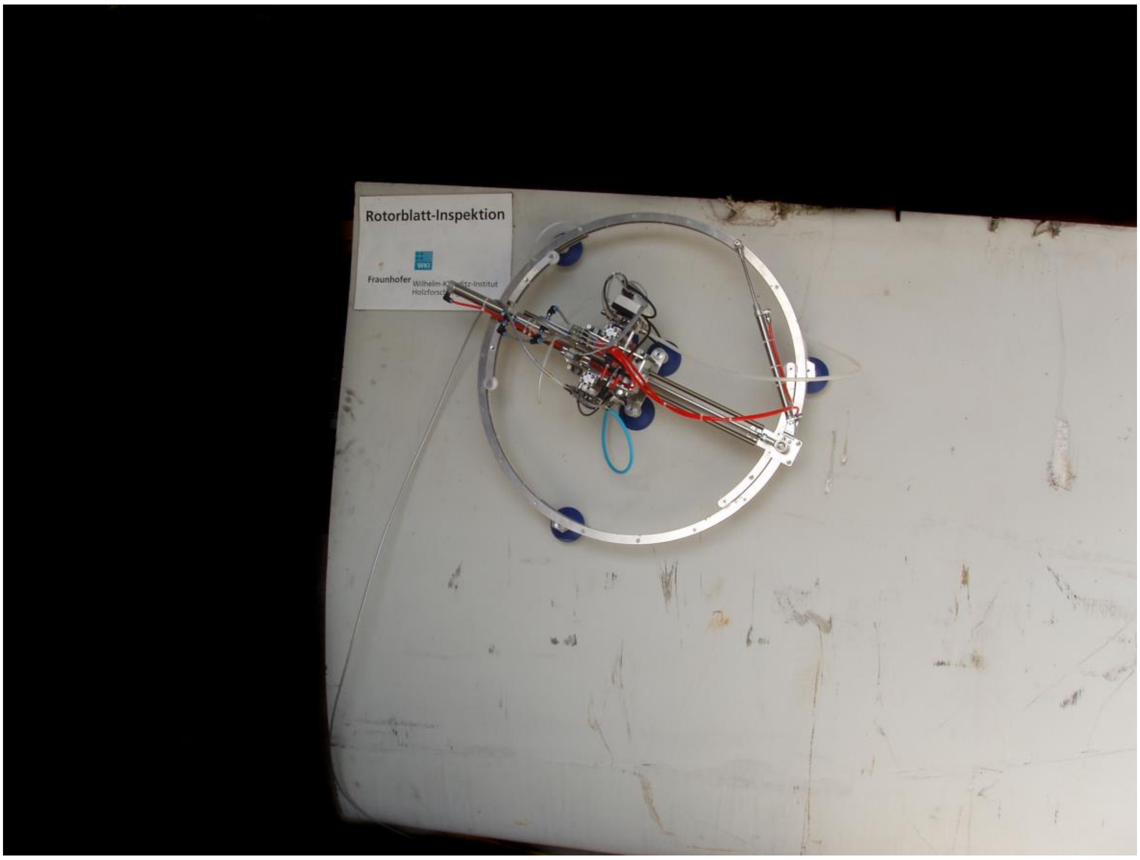

Figure 2. 9: The robot during the motion test process at the facilities of Fraunhofer WKI. The picture clearly shows the surface cracks and other defects of the blade. (Source: Idaswind GmbH photo archive)

The problem though was not only caused by the passive step sensor system but also because of the design of the vacuum cups. They were not really flexible and their elastic part was very hard, therefore they could not attach to any surface if it was not perfectly smooth. Additionally, since the vacuum cups could not really seal their contact surface with the blade surface due to the scratches, the vacuum pumps had to renew the vacuum every 10-15sec. Naturally, the bigger the surface damages the longer the time that the vacuum pumps were running. Finally in the case of sever damages and delamination the vacuum cups could not produce any vacuum and the robot was in danger of detachment.

At the motion domain of the robotic platform, the tests on the blade revealed some new parts for further investigation and development. During a real blade inspection process, the robotic platform with the NDT sensors should be able to move precisely and in small steps in order to scan the surface, but also to move fast in order to move from one point to another in the shortest time. The second requirement was achieved with the fast and powerful pneumatic cylinders, but the fine, precise movement could not really be realized. Some sort of sensor should be installed in order to allow a precise and reliable measurement of the motion.

### 2.3 Robotic Platform Development (Version 2)

The 2nd Version of the robot had to improve all the previous deficiencies of the initial prototype in all the aspects, structural, mechanical, control and electronic. It was therefore obvious that the current design had limited capabilities as a robotic platform, therefore a totally new design should be developed. The final decision was to keep the strong points of the old design and integrate them in the new design in order to achieve and generally improved robot. Additionally this new robot would be completely modeled in a 3D CAD software (including cabling and tubing) in order to reduce the developing time (and cost) by correcting any mechanical and kinematic problems before they would be realized.

Figure 2. 10: Computer generated 3D model of the 2nd Version of the robot attached on the inclined test surface. (Source: Idaswind GmbH photo archive)

*The mechanical structure*

A completely new ring frame structure was designed and manufactured with new central (linear) unit and new main frame. The whole robot was now slightly bigger in dimensions and significantly stiffer since all the parts were oversized. Of course as a side effect, the weight of the main structural platform was increased, but the increased mechanical strength enabled the installation of bigger and much stronger pneumatic cylinders, which made the robot much more powerful and fast. The necessity of the CAD designing process was apparent during the designing phase when, many small problems could be identified and solved. Finally, when the robot was manufactured and properly assembled it had no colliding parts or mechanical problems.

*The Motion and Control*

Due to the stronger linear pneumatic cylinder, the robot was accelerating strongly while moving linearly. This feature was causing a rough motion pattern and very high stresses at the mechanical structure. In order to prevent fatigue damages of the mechanical parts and even worse failures at the control electronics two pneumatic brakes with special brake pads were integrated in the main frame structure and their job was to bring the slider to a halt before it would reach the end of the sliding rail. This was not a difficult task for the control system, but it needed some additional inputs in order to estimate the position of the linear slider.

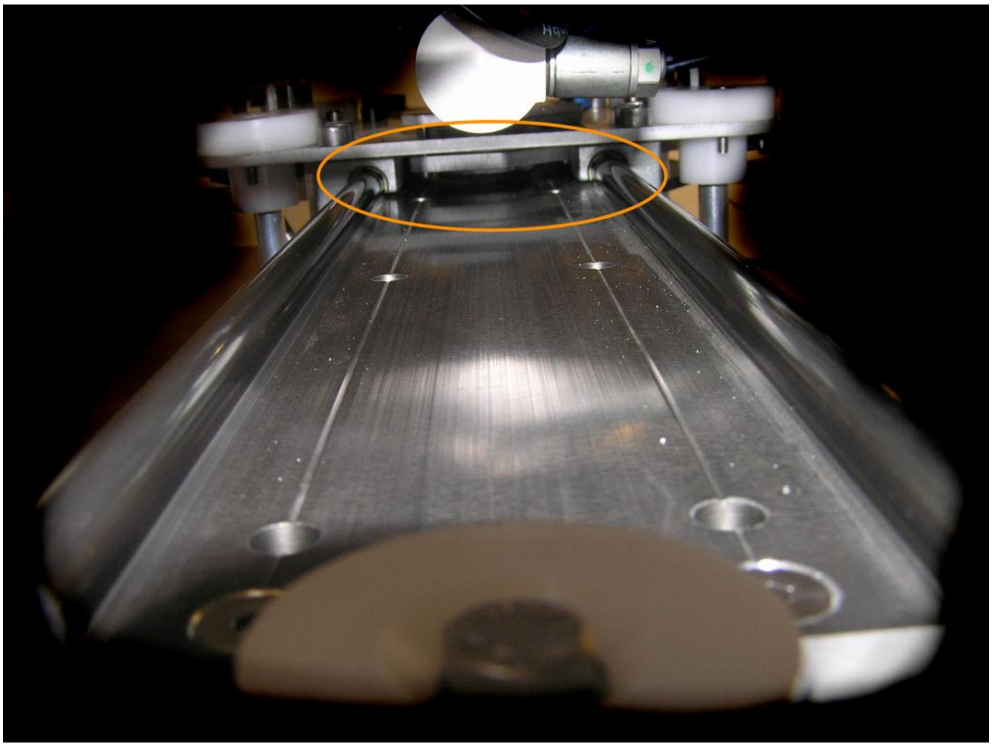

Figure 2.11: The picture above depicts the pneumatic brake of the main slider which presses a custom made brake pad on the sliding rail surface. The linear cylindrical shaped sliders and their guides are also clearly visible. (Source: Idaswind GmbH photo archive)

The implementation of a linear position sensor was necessary and after some product research, the sensor matching best with the needs of the robot was an incremental inductive sensor with its magnetic measuring tape installed at the sliding rail structure. This sensor enabled the precise measurement of the position of the main slider and then the calculation of the slider's speed and acceleration. These measurements were really valuable since the progressive braking could be adapted to the current velocity of the slider and achieve a smooth braking action.

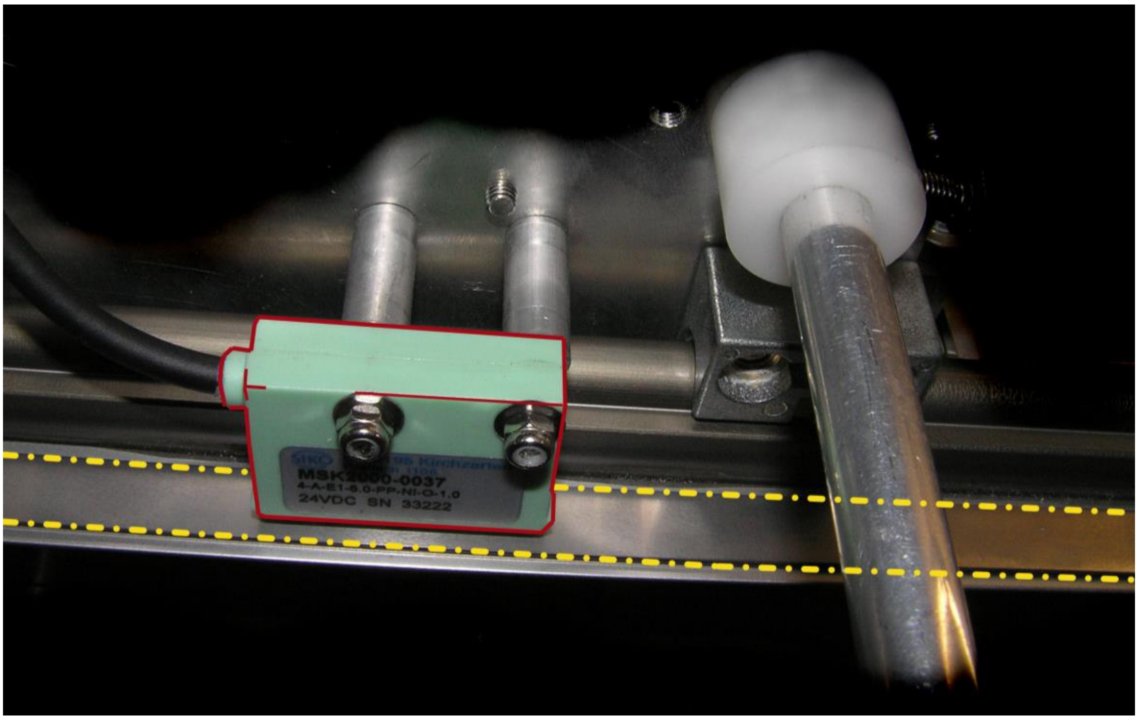


Figure 2.12: The magnetic stripe (marked with yellow lines) allows the precise position measurement by the induction sensor (marked with red lines). (Source: Idaswind GmbH photo archive)

In order to enable a better stepping ability on curved surfaces, the outer vacuum cups were replaced with softer cups (double folded) of the same outer diameter. This change did not affect the motion patters but the new cups enabled the robot to attach to curved and uneven surfaces with more success.

Figure 2.13: The two different types of vacuum cups. The rigid (left) used for the inner sliding unit and the flexible (right) used for the outer ring unit. (Source: Idaswind GmbH photo archive)

The individual electronically controlled air-valves of the past could not come with the new situation. The solution for this problem was the introduction of the ‘valve island’ unit (from FESTO) which provided 12 valves integrated in one complete valve unit with universal control system through an RS232 cable. Additionally a circuit board was designed and manufactured in order to integrate the automation subsystems such as the valve unit and the vacuum pumps into a general control unit. This control unit was equipped with a programmable micro-controller and a Bluetooth wireless communication system. Therefore the complete control system was able to communicate with the base terminal without long and heavy data cables.

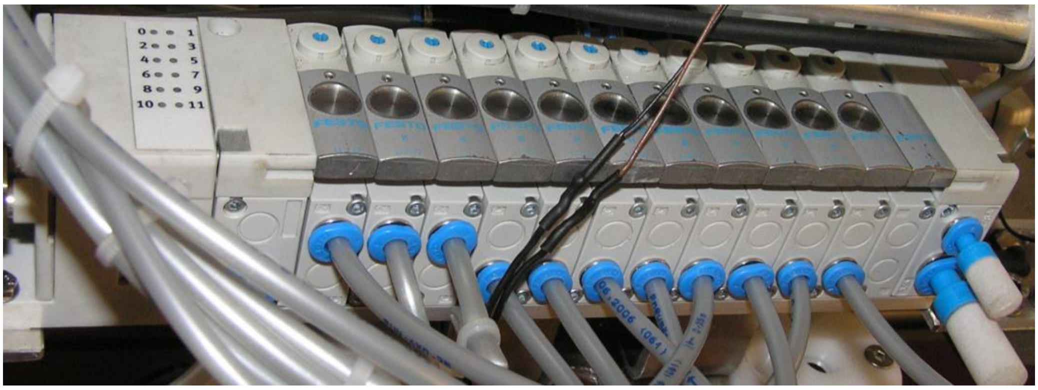

Figure 2.14: Integrated multivalve unit with RS232 computer data bus from FESTO.
(Source: Idaswind GmbH photo archive)

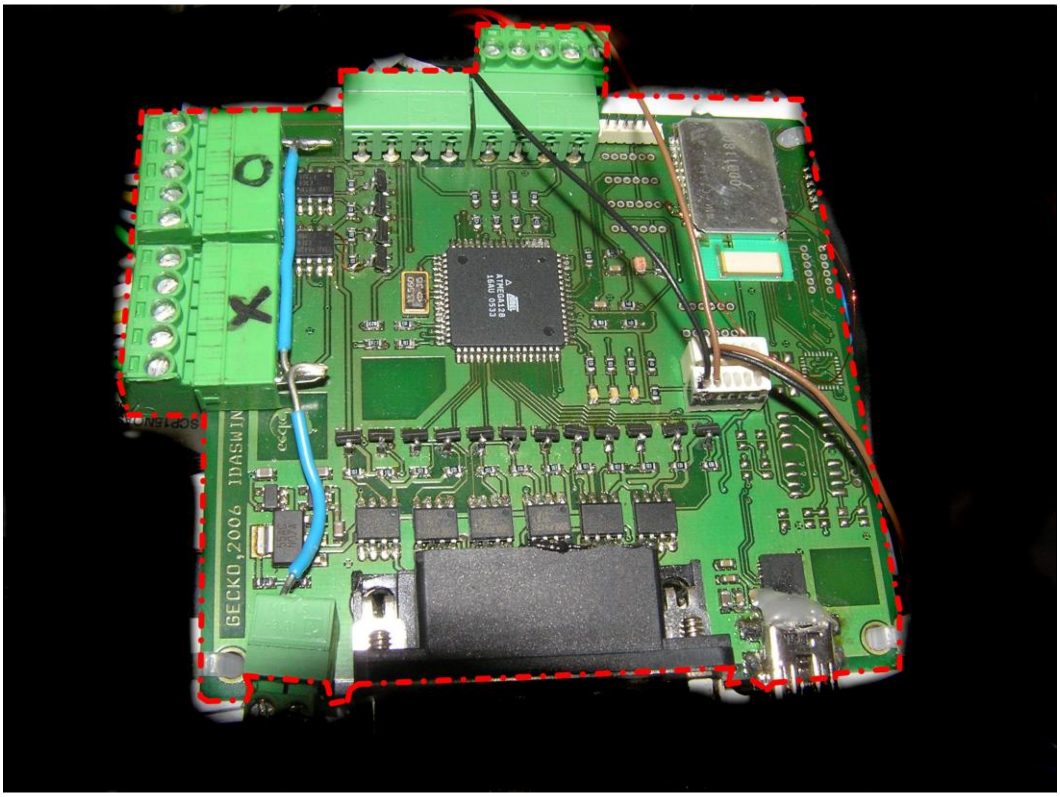

Figure 2.15: Custom made control circuit board from Naventics GmbH. It integrates the control microprocessor (center), the wireless Bluetooth unit (top right) and the communication inputs-plugs.
(Source: Idaswind GmbH photo archive)

The next step at the development process of the robotic platform was the implementation of mechanically activated electric step sensors. As it was mentioned before, the stepping process was using passive means of monitoring, through the measured vacuum level at the vacuum cup system. However the test revealed many system flaws and in practice this simple method could not be used. The simplest alternative would be the implementation of mechanical stepping sensors which would identify the contact of the vacuum cap with the blade surface and send a signal to the control system. In case of a firm contact between the blade and the cup, the control would switch on the vacuum pumps in order to achieve the attachment of the robot to the blade. If the contact was not confirmed by all the stepping sensors, then the control system would perform a step back and a slight turn in order to find a more adequate stepping place. This concept was tested in the lab and the results were positive, therefore these mechanical telescopic stepping sensors were finally implemented at the model.

Figure 2.16: Computer generated 3D model of a telescopic contact sensor and its mounting base. (Source: Idaswind GmbH photo archive)

All these changes in the mechanical part of the robot made the whole construction much more complicated and demanding in terms of control programming and pneumatic automation.

## 2.4 Robotic Platform Testing (Version 2)

The robot was imposed to several performance tests at the test facilities of Idaswind GmbH in order to investigate the performance of all the new development achievements. The test period was relatively extended in order to reveal additional fatigue problems or possible problems of the bolted assemblies. The general outcome of these tests was positive and proved that the developing process of the robot was heading to the right direction. However some problems inevitably occurred and additional tests were performed in order to locate the source of the problems.

One of these problems was the complex and slow turning motion of the robot. As it was described above the robot would change its elevation constantly in order to perform the incremental turning motion. These intermediate steps would significantly slow down the robot resulting in a significant time loss in the future scanning process of the complete turbine. Additionally the elevation changes would increase the probability of a step on a crack which would therefore mean that the turning process would stop. Especially this problem was much more crucial because it could lead to ‘dead end’ situations. In other words, due to the fixed rotation step angle (which is defined from the pneumatic cylinder’s length) and the stepping process, the robot could be trapped between two areas with cracks, or between a crack and the blade edge without any possibility of escaping.

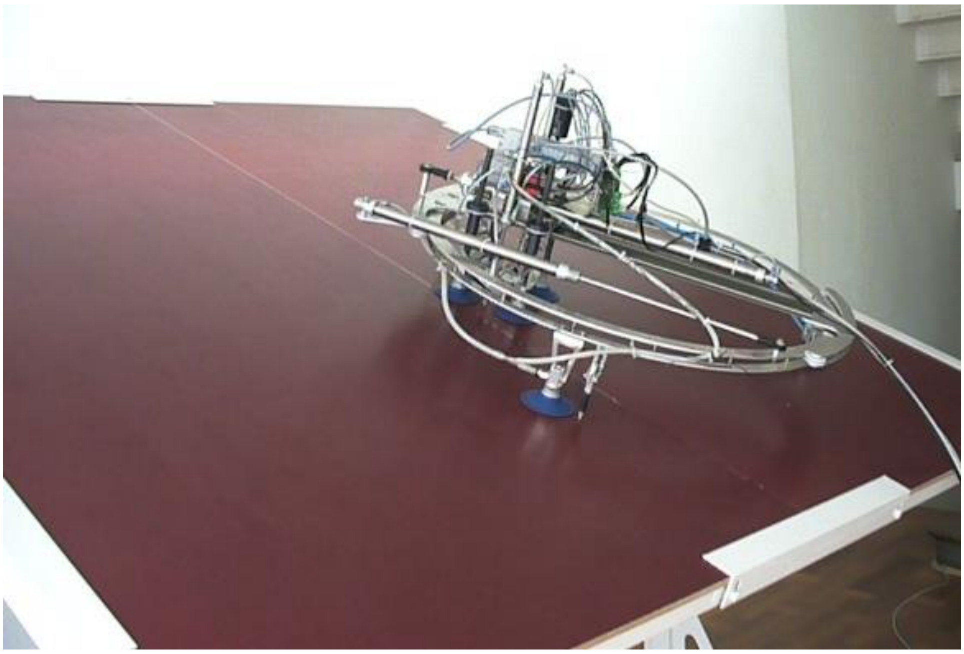

Figure 2. 17: The robot during the extensive test period at the lab facilities of Idaswind GmbH. (Source: Idaswind GmbH photo archive)

In order to investigate this possible problem, the robot was placed near the edge of the test surface at the lab with its motion pattern being independent from the user (autonomous motion). In some cases the robot performed many random motions in order to get away of the bad situation but in the end it was not able to escape. This proved that the turning system should definitely be replaced by a much more flexible and fast system which would enable the robot to move autonomously on the blade surface without the danger of getting in a ‘dead end’ situation.

The lab tests also involved motion tests of vertical surfaces and even a few motion tests on surfaces with negative inclination (up side down). These tests produced valuable results since they revealed some technical problems that were undetectable before. The most important of these problems had to do with the mechanical stepping sensors that were installed on this version of the robot. In theory the frame of the robot was stiff enough in order to prevent the deformation under it own weight. However when the main slider was located at the end of the sliding rail and while the rail orientation was vertical with the main slider being at the lower side, the upper side was unloaded and not supported properly. The consequence was the appearance of structural flexibility which caused several problems during the walking process.

Figure 2. 18: Under some circumstances, the bending moments would cause the deformation of the ring frame. When this deformation was occurring at a vertical surface, the outer vacuum cups of the stepping sensors were not able to attach to the surface. (Source: Idaswind GmbH photo archive)

When the walking plane was vertical, the vacuum cups were able to have good contact with the surface but the stepping sensor, which was placed in the outer perimeter of the vacuum each cup could not attach to the surface (only the one which was at the upper position would attach). As long as the signal of ‘positive contact’ of the stepping sensors did not come to the control system, it was assumed that the robot had reached the edge of the blade and could not continue its way. However this was a fault signal caused by a structural weakness and not a problem with the sensor itself, therefore the need for further re-design arose. Either the sensoring concept should me modified or the structure of the main frame of the robot should be much stiffer.

Another small problem which was apparent only after some long duration tests was the loosening of some of the screws. Since the robot was assembled with screws and bolts and due to the strong vibrations and high stresses, some of these bolts became loose. An incident of this nature led to the release of one roller during the testing process. Since the roller was detached from the robot, the outer ring was partially destabilized and the test had to stop at once for a fast repair. Although the situation was not critical during this incident due to the controlled lab test conditions, in ‘real life’ situations a minor incident like that would probably lead to the detachment of the robot from the rotor blade, with possible damages for both the robot and the blade.

## 2.5 Robotic Platform Development (Version 3)

*New turning pattern*

The continuation of the development process started immediately after the test period of the 2$^{nd}$ Version of the robot. There were many obstacles to overcome and many improvements had to be made. The most important problem that had to be attacked was the turning process of the robot. The final idea came up after long brainstorming sessions and was clever in the sense that it would maintain the same basic structure of the robot while in the same time it would enable the robot to turn without changing its stepping mode. Additionally the rotational angle had no limits from the mechanical structure while it was significantly faster than before.

The idea was based on a human activity imitation pattern, more specifically the imitation of the steering wheel turning action. The human drivers perform a turn of the vehicle by turning the steering wheel and this is done by a continuous alternating grip of the steering wheel. Therefore when one hand grabs the wheel and turns it, the other is released and grabs the wheel again at the end of the stroke of the 1st hand. Consequently the robot had to be equipped with mechanical devices that would allow this pattern to be performed. Also the turning piston should be mounted on two moving units, one of which was the already existing main linear unit. The 2nd unit should replace the fixed connection of the piston with the ring frame and it should be able to move along the perimeter of the ring structure.

The movable endpoint of the pneumatic piston was finally formed as a rolling plate equipped with 3 pulley-like rollers, which would engage the top aluminum blade of the ring structure and allow the rolling plate to securely follow its circular path with the least amount of friction between the ring frame and the rolling plate. The rollers were manufactured from (POM) plastic in order to reduce the friction with the aluminum ring frame and they would rotate with plastic bushings on aluminum shafts with low friction coatings. Thus the whole system was virtually frictionless and enabled a smooth motion. The rolling plate was also equipped with a pneumatic brake piston which would press a custom made brake pad on the ring frame surface and perform the braking action. The extendable end of the pneumatic cylinder which performs the turning action of the robot was mounted on the rolling blade by means of a spherical joint, with the spherical bushing being from self lubricated plastic materials.

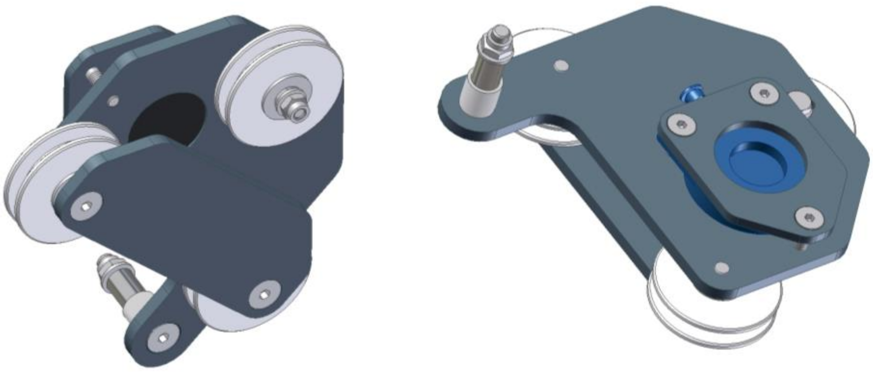

Figure 2. 19: The secondary angular unit equiped with plastic rollers and pneumatic brake.
(Source: Idaswind GmbH photo archive)

*New stepping sensors*
The aforementioned problems with the stepping sensors during the last test session demanded some sort of new, innovative solution. However this task proved to be much harder to achieve than it initially seamed. The developing process started with the telescopic mechanical sensors. However as the test revealed, these sensors could not perform properly when the robot was moving on vertical surfaces. The next step was the improvement and optimization of this mechanical sensor concept. New 3D models of stepping sensors were created and a final design was selected for the prototype production phase.

The prototype of the new stepping sensor was manufactured at the workshop of Idaswind GmbH and consisted of a robust and durable telescopic mechanical module, which would activate an inductive switch in order to perform the stepping sensor process. This design combined the reliable mechanical construction with the friction-free and reliable inductive switch. Being equipped with longer telescopic legs would be able to make contact with the blade surface in vertical motion conditions. Finally, the inductive switching action would not require further modifications of the electronic and control circuit board, thus reducing the development costs and offering a simpler approach.

Figure 2. 20: One of the modeled and simulated alternative concepts for a stepping sensor configuration. The metallic lever is rotating around an axis and activates the inductive switch.
(Source: Idaswind GmbH photo archive)

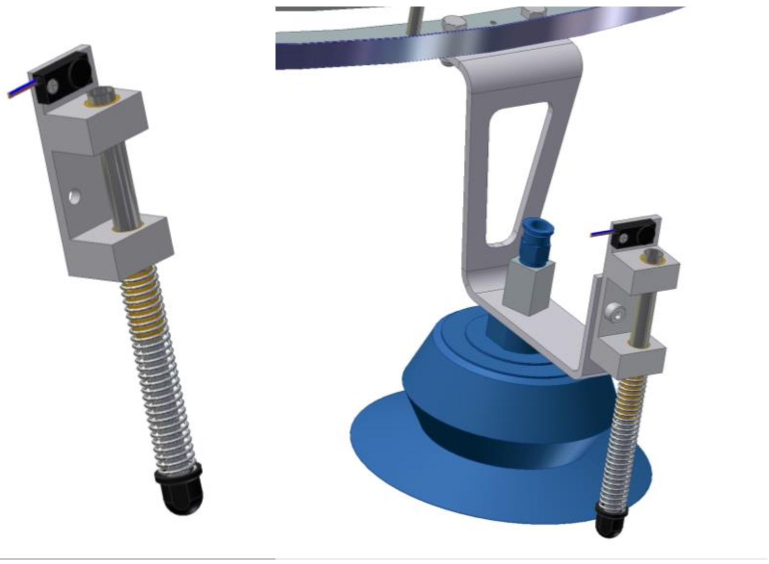

Figure 2. 21: The new custom made telescopic stepping sensor with the secondary inductive switch on the top. The variable mounting point of the sensor is located on the modified leg.
(Source: Idaswind GmbH photo archive)

The material selection for this new sensor was made in such a way that the manufacturing process would be cheap and robust but in the same time a very low static friction of the telescopic sliding parts would be achieved. The materials used for the sliding parts were stainless steel and brass bushings, while aluminum and (POM) plastic were used for the sensor main body. The sensor's spherical tip was manufactured from (POM) plastic in order to prevent blade surface damage while stepping. The final assembled sensor proved to be really durable and its switching operation seamed to work fine, therefore it was installed on the robot for further tests.

*Pistons with damping system*

New pneumatic cylinders were ordered from FESTO in order to replace the previous ones. The new cylinders were equipped with built-in adjustable pneumatic damping systems, which allowed the fine tuning of the deceleration of the piston towards both ends of its travel. The damping systems were tuned during motion tests and after the tuning process all the movements of the robot became much smoother. The result of this development step is much bigger than it seems since the smoother motion increases significantly the reliability of all the mechanical and electronic subsystems, which no longer suffer from sever shocks and vibrations.

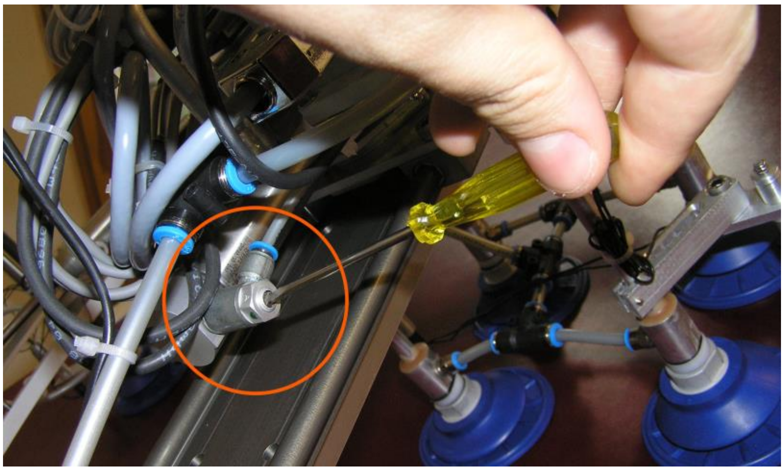

Figure 1.22: Tunning of the damping system of the pneumatic cylinder.
(Source: Idaswind GmbH photo archive)

*Variable and Progressive Braking*

Another step in the development process, which reduced the motion vibrations and shocks was realized in the domain of braking. Initially the main slider was equipped with two pneumatic brakes which would be activated when the slider would reach the end of its travel. However the immediate brake activation would lead to the immediate deceleration of the slider and high mechanical stresses on the structural and electronic components of the robot. The solution to this problem was the implementation of a progressive and variable braking system. Therefore one brake maintained its initial operation while the other was programmed to operate incrementally depending on the sliders velocity (measured by its magnetic sensor). Therefore the progressive brake would be initially activated in order to gradually decelerate the slider from its top velocity and the second brake would act as a park brake, which would insure the positive and secure braking of the decelerated slider. The fine tuning of this system was a long process, which involved continuous testing and re-programming of the control unit. However the final positive results prove the usefulness of the progressive braking concept.

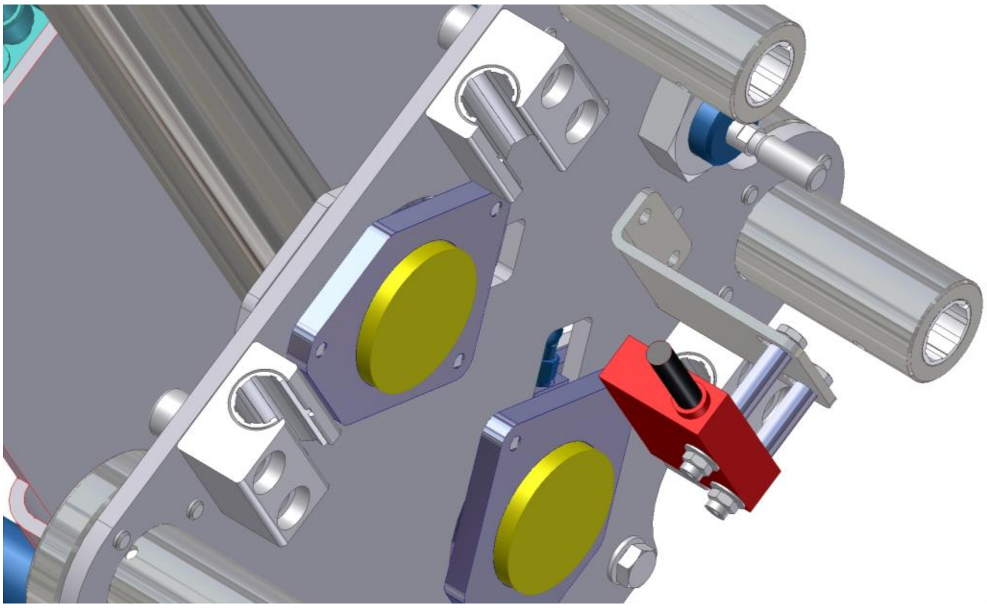

Figure 2.23: 3D model of the main sliding unit viewed from bellow. The two braking units are mounted on the main base plate and are equipped with custom made brake pads (yellow colors).
(Source: Idaswind GmbH photo archive)

Figure 2.24: The pressure regulating valves of the progressive pneumatic brakes.
(Source: Idaswind GmbH photo archive)

*Cable guiding systems*

The final development step involved a less crucial but nevertheless important task, the cable and tube guiding system on the robot. Elastic bending structures were created from spring steel rods in order to support the cables and air pressure tubes of the robot. Each pneumatic cylinder was equipped with a system of this type in order to securely guide the cables and air pressure tubes during the robot operation. Additionally another guiding system was created in order to provide vacuum from the vacuum pumps (mounted on the main slider) to the outer suction cups mounted on the outer ring frame. This system was much harder to achieve since it should enable the slider to move in all the possible positions inside the ring frame area and in the same time enable the slider to rotate freely. The demand for free rotation was the hardest to achieve since the problem becomes more topological than mechanical. The final technical solution was a compromise between turning freedom of the robot and topological restrictions of the cable guiding system. Finally the cable guiding systems of the robot, restricted its turning abilities to 359°, which however was considered to be sufficient for the use of the robot.

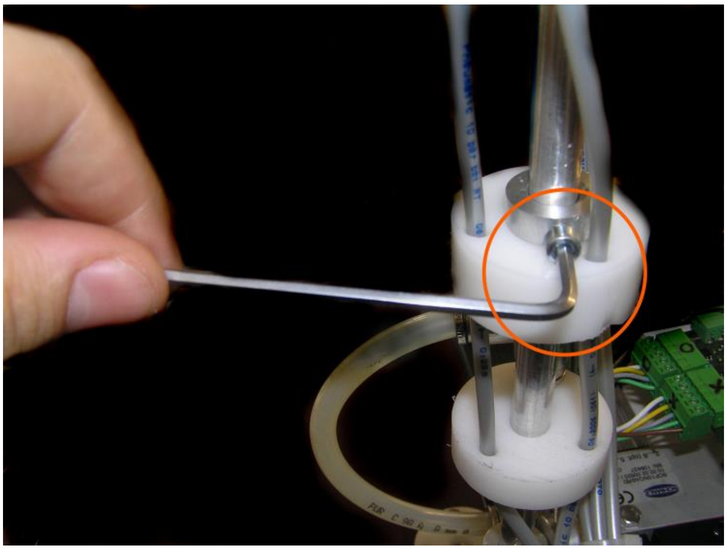

Figure 2.25: Adjustable cable guiding system for the main air pressure tubes of the robot. (Source: Idaswind GmbH photo archive)

### 2.6 Extended lab tests and tests at Fraunhofer WKI (Version 3)

The developing and tuning process described above included many component test in the lab facilities of Idaswind GmbH. However after the completion of the 3rd Version of the robot, a long test session started in order to reveal possible problems and disadvantages of the newly implemented techniques. The tests started at the lab facilities of Idaswind GmbH and concluded at the lab test facilities of Fraunhofer WKI.

In general the robot showed a very good performance in various surfaces and various angles of operation. During the lab tests at Idaswind GmbH, it was able to work continuously for long periods (more than 2 hours) without any failure in the mechanical or electronic systems. After the first long time tests, the control system was set to random motion, where the robot moves towards random directions. The robot was attached to the inclined platform of the test lab, with the platform surface in vertical position and it ran randomly for about 3 hours. Its control system with all the stepping sensors enabled the trouble-free operation in confined areas since the robot was able to avoid stepping over the edges.

The only slight problem of the robot after the 3 hour motion test was related to the plastic rollers of the main rotational unit and the angular rotating cart. Apparently the friction between the roller and its shaft and the vibrations and bending moments of the whole structure were able to slightly un-tighten the screws of the roller shafts. However this was just a minute problem which could be solved easily with the implementation of some adhesive material during the tightening process of the screws (e.g. Loctite). Apart from that small incident the robot was performing astoundingly well and it seamed that the design was in the right path. After these positive results during the lab test period, more realistic tests were performed in order to prove the functionality of the robot. The next test session was scheduled for the 2nd half of November 2006 and it was realized at the lab facilities of Fraunhofer WKI institute. This lab was equipped with various surfaces but most important, with a 10m part of a used wind turbine blade. This blade part provided all the necessary angles and surface conditions in order to estimate the performance of the robot in real life conditions.

The results from the test on the blade were very interesting even though they were not as positive as the results during the lab tests. The robot did never detach from the blade surface, but in several occasions it was unable to move. The causes for this problem were many and of different nature and affected either the software or the electronic control system. One common cause was the incident of continuous stepping on cracks which baffled the software of the robot causing continuous false movements or looped motions. This problem was mostly caused because of the control software of the robot which orders the robot to step back and perform a 50° turn when it steps on a crack (or bad surface which cannot provide vacuum). Due to this ‘single step back’ command and the fixed turning angle command (50°) the robot could not perform the ‘step back’ motion because the vacuum caps of its other unit would step again on a crack. But again after canceling the ‘stepping back’ motion, the robot would step front and turn again 50° in the opposite direction, thus stepping again on the initial crack. When something like that would occur, there would be no way out of the loop.

Apart from the fact that a more sophisticated motion pattern was needed, it was also necessary that the robot was able to create vacuum and safely step on surfaces that have some minor cracks. The flexible outer vacuum cups of the robot were generally tolerant against small cracks even though their vacuum consumption was increasing every time they were stepping on a crack. However the more rigid internal vacuum cups were unable to tolerate even the smallest cracks, therefore a great number of steps, which would be possibly successful, were aborted due to the inability of the central vacuum cups to create sufficient vacuum.

Another problem and possibly the most important of all was the inability of the robot to move over strongly curved surfaces. In slightly curved surfaces, the outer vacuum cups, were able to bend and align with the blade surface, but the rigid inner cups were not able to bend, therefore their sealing ring would deform thus preventing the formation of sufficient vacuum. The robot was practically unable to get close to the leading edge of the blade, even though it could easily move on less curved surfaces (like the blade root). The problem was even more crucial then the robot tried to move on negative curved surfaces, like the cambered side of a blade close to the root. There the outer cups would bend and step on the surface, but in the same time try to bent the central unit as well. Since the vacuum cups of the central unit could not perform well, they were deformed and they would loose the vacuum and in order to avoid the complete detachment of the robot, the control would cancel the step and lift up again the ring structure.

## 2.7 Robotic Platform Development (Version 3.5)

*New mechanical design*

The next steps in the development included the introduction of an almost new version of the robot rather than some minor upgrades. The main development issue was the ability of the robot to move on highly curves surfaces of both positive and negative curvature. The current design had reached its limits regarding the possibility of attaching on curved surfaces and the only possible change, which would improve the current situation was the replacement of the four central rigid vacuum cups with four new flexible ones (identical to the ones of the outer ring unit). However this was not enough and in order to achieve the goal, many significant changes had to be made. At the same time the main mechanical design should remain virtually unchanged in order to reduce development costs; which also meant that the custom made control unit should also remain unchanged. This last requirement was causing the strictest limitations on the development process.

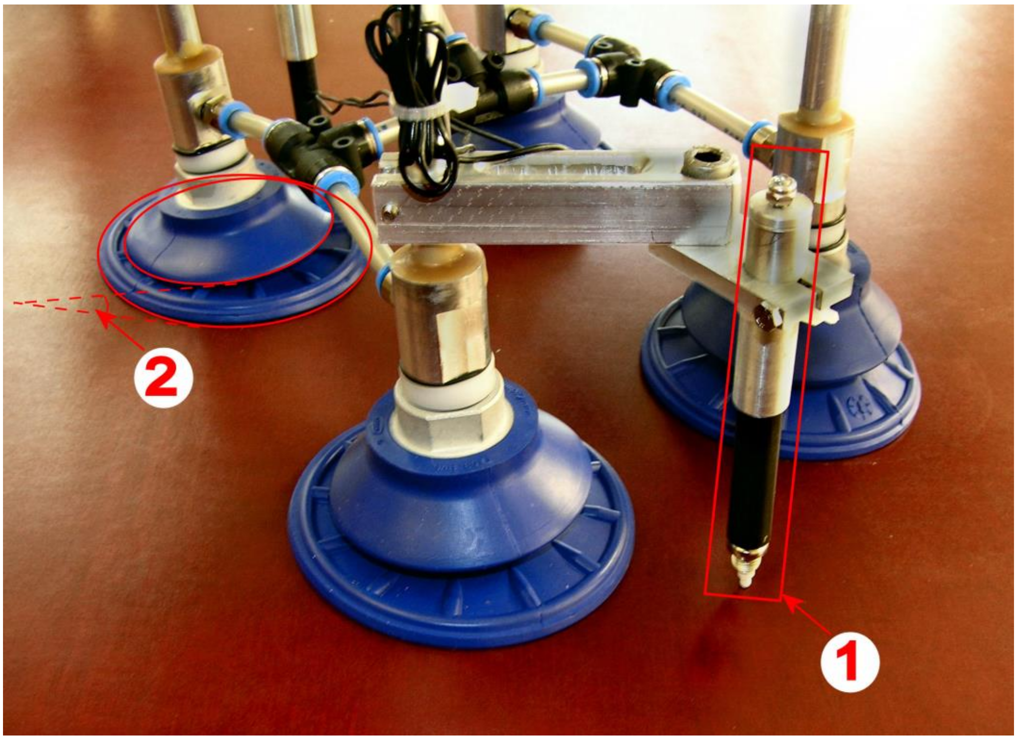


Figure 2.26: New flexible vacuum cups (2) for the central sliding unit and new mounting bases for the initial mechanical stepping sensors (1). (Source: Idaswind GmbH photo archive)

After intensive brainstorming and rough computer modeling of the most promising ideas, the final concept was developed. The final concept was neither the most sophisticated of all nor the most robust, it was however the only idea which could achieve very good kinematics with the minimum possible cost and the shortest possible development time. According to this idea, the extendable internal legs of the robot are replaced from rigid units, equipped with four flexible vacuum cups. The outer rigid legs are replaced by more flexible leg structures with extendable vacuum cups. These new outer legs are much more sophisticated and combine various semi-flexible parts in order to achieve an increased flexibility of the outer cups.

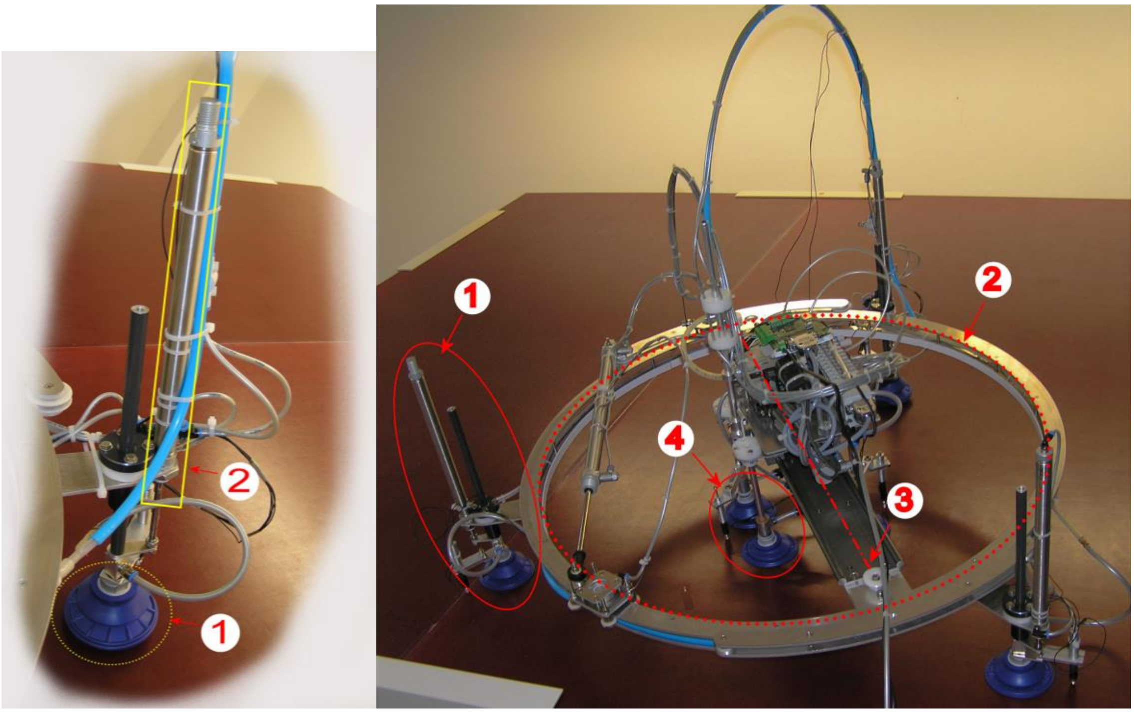


Figure 2.27: (Left Image): The new outer leg structure with the flexible vacuum cup (1) mounted on the coated linear slider and the pneumatic cylinder (2) mounted on the AlMg base plate. (Right Image): View of the 5th Version of the robot with the new outer leg units (1), the new inner leg units (4) and the remaining ring frame (2) and linear sliding rail (3). (Source: Idaswind GmbH photo archive)

Specifically, the outer leg structures consist of three flat 3mm thick plates of AlMg, which have been precisely formed by a laser-cutting CNC machine. These plates are bolted on the ring shaped frame of the robot and extend radially outwards. The outmost parts of these base plates host the pneumatic cylinders and the linear sliding bushings (linear guide) which engages the low friction sliding rod with the vacuum cup bolted on it. The pneumatic cylinder provides the linear force and the sliding rod with the plastic bushing receive all the loads that are not coaxial with the pneumatic cylinder motion. The vacuum cups at the ends of the sliding rods are flexible and allow a good level of tolerance against some surface irregularities. However, the high curvatures and the bigger surface irregularities are handled by the combined flexibility of the vacuum cups, the leg base blades and the locally deformable ring frame unit. The final result in terms of curve handling ability is astounding, since the robot is now able to achieve good adhesion on strongly curved surfaces. The most important aspect of this concept though is the fact that the control unit and the stepping sensor circuit remains 100% unchanged thus eliminating any extra development costs from this domain.

*Dimension confinement*

Being the pneumatic cylinders on the outer perimeter of the ring meant that everything else should be confined inside the imaginary circle defined by the outer legs' cylinders in order to allow the robot to turn freely. The previous concepts incorporated a 500mm long linear pneumatic cylinder, which was responsible for the linear motion of the robot. This cylinder would extend approx. 400mm out of the ring's outer diameter when the piston of the cylinder was in the extended position. Since the turning action of the robot with the main cylinder in the extended position was not feasible, the linear motion system had to be redesigned. The new system makes use of the incremental turning concept which is now used for the linear motion of the main sliding unit. The new pneumatic cylinder is only 250mm long and its moving side is not fixed at the linear rail unit, but it is mounted on a linear sliding plate. This plate is also equipped with a pneumatic brake and enables the incremental movement of the main sliding unit of the robot. The linear motion is now performed in two continuous steps, with slightly reduced overall linear velocity, but on the other hand the linear motion is much smoother since the acceleration of the sliding unit is not very high. The final result is a trouble free turning operation, and a smoother and acceptably fast linear motion.

Another modification of the initial design involved the mounting point of the turning cylinder of the robot. Initially this cylinder was mounted on the rolling platform (piston side) and an extension of the structure of the linear unit. This extension was created in order to improve the leverage of the pneumatic cylinder and to increase the turning torque of the turning unit. However the new position of the outer legs of the robot would cause collisions between the outer legs and the extension, therefore the extension had to be machined in a milling machine in order to remove it and re-mount the pneumatic cylinder in a suitable position. The modified system has a less favorable leverage but since the pneumatic cylinder that performs the turning action is oversized, there is no problem in the kinematics of the robot.

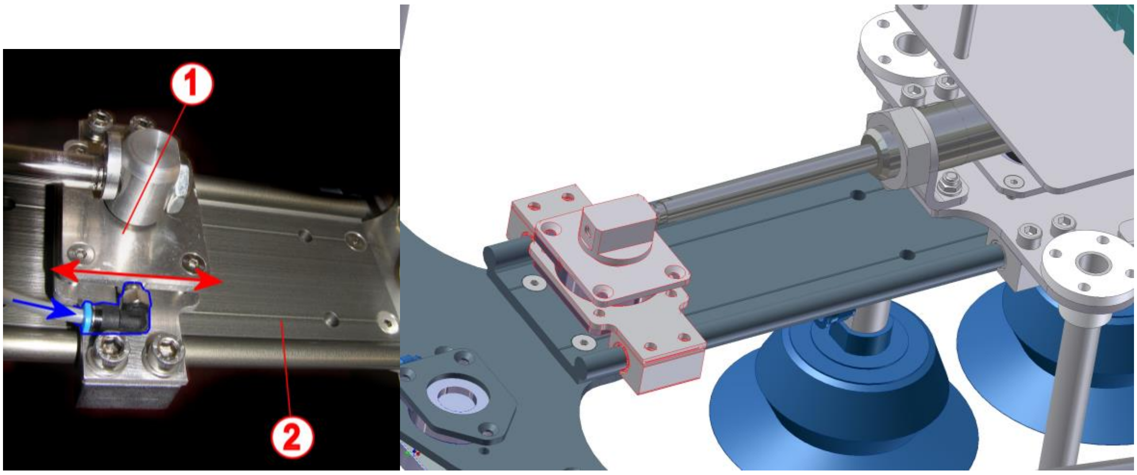

Figure 2.28: The new incremental motion linear system, equipped with the additional sliding unit (1) which slides on the initial linear slider (2). (Source: Idaswind GmbH photo archive)

*Total sliding angular units concept*

The problem of the bolt loosening of the rolling angular units was another important issue which should be solved in an efficient and reliable way. The proposed solution to this problem has the potential to solve more than one problem at the same time. It introduces the sliding concept to the project and completely eliminates the use of rolling or moving elements. This new concept replaces all the existing rollers with universal, custom made, low friction sliding assemblies which are designed to fit to the old mounting points of the plastic rollers. The basic idea of the sliding principle is simple; however the final universal sliding unit has to combine many different design, manufacturing and operation aspects. It should be a low cost solution which manufactured at the workshop of Idaswind GmbH, but at the same time it should offer superior kinematics and performance characteristics to the old roller concept. Finally it should be able to cope with the small irregularities of the profile of the ring shaped sliding surface. These irregularities were created from the laser cut process during the manufacturing of the ring shaped frame and they were not evened due to cost reduction techniques.

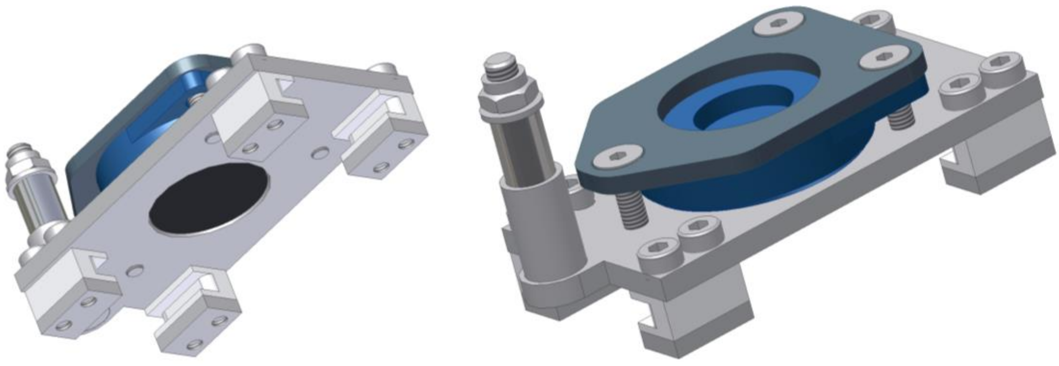

Figure2.29: Views of the initial design for a sliding turning unit. The design was realized and the slides were machined from POM plastic. (Source: Idaswind GmbH photo archive)

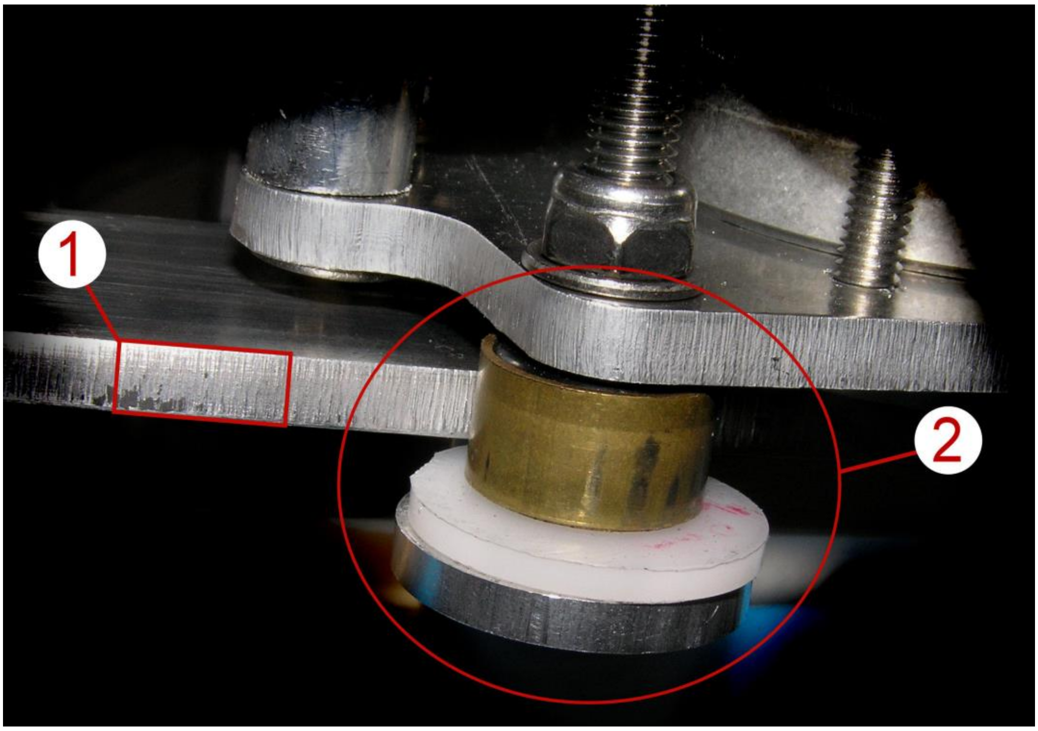


Figure 2.30: The small irregularities (1) of the vertical surface of the ring frame posed special design characteristics for the universal sliding units (2). (Source: Idaswind GmbH photo archive)

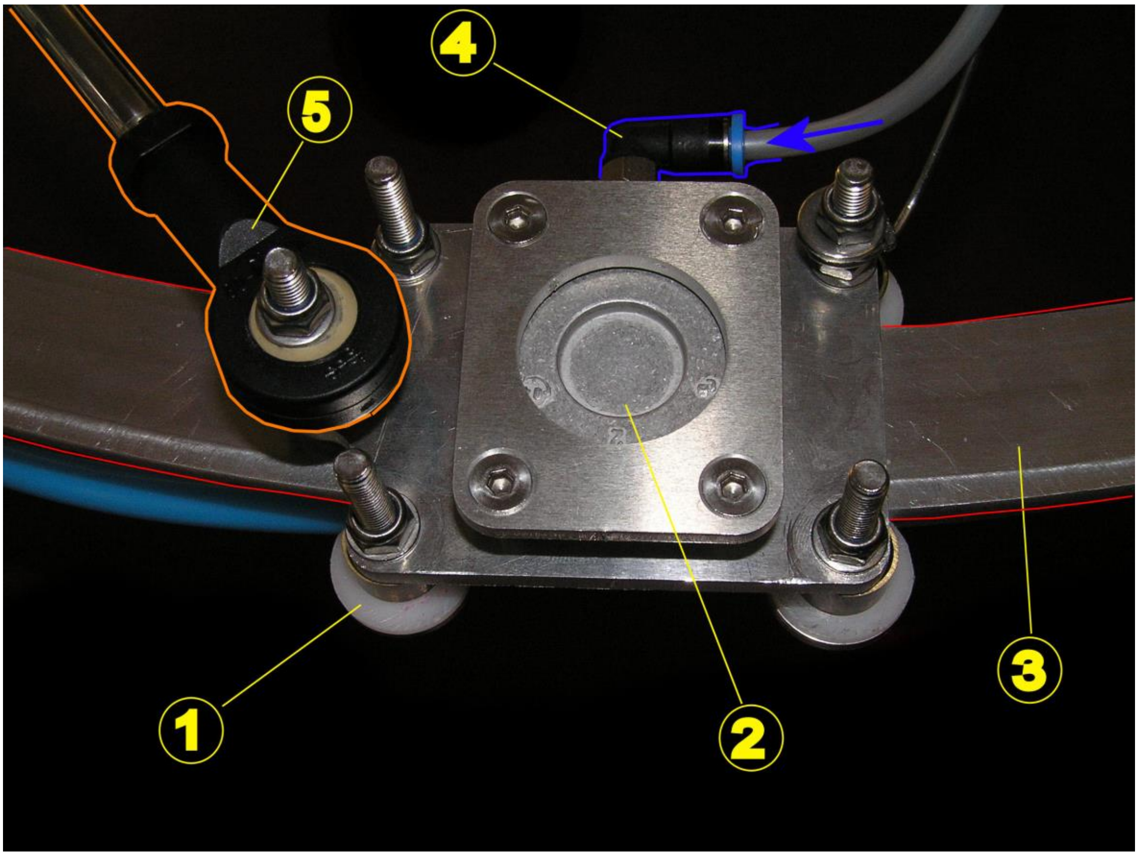


Figure 2.31: The new design for the small angular sliding unit consists of the universal sliders (1) and the pneumatic brake (2). The turning cylinder is connected to the sliding unit through a plastic spherical joint (5) and moves the sliding unit along the ring shaped frame (3). The air pressure tube (4) is used for the activation of the pneumatic brake. (Source: Idaswind GmbH photo archive)

The final universal sliding units successfully fulfilled all the abovementioned demands and they have already proven their functionality. The central aluminum core was machined from solid aluminum and the machining process involved only some straight passes, two o-ring groves and a central hole with one tapered end. The horizontal sliding surface was created by a 1mm thick plastic (POM) ring, machined at the lathe to fit inside the extruded cylinder of the central part. The radial sliding surface was created by an off-the-shelf brass tube cut in size and fixed with two o-rings on the central part. The double cylinder perimeter contact (line contact) offered very low static and kinematic friction with the ring frame, while the o-rings were able to absorb the small irregularities of the laser cut surface of the ring frame. The performance of the universal sliding units proved to be better than expected and the friction of the system during the turning process is possibly even lower than before (during the operation with the rollers).

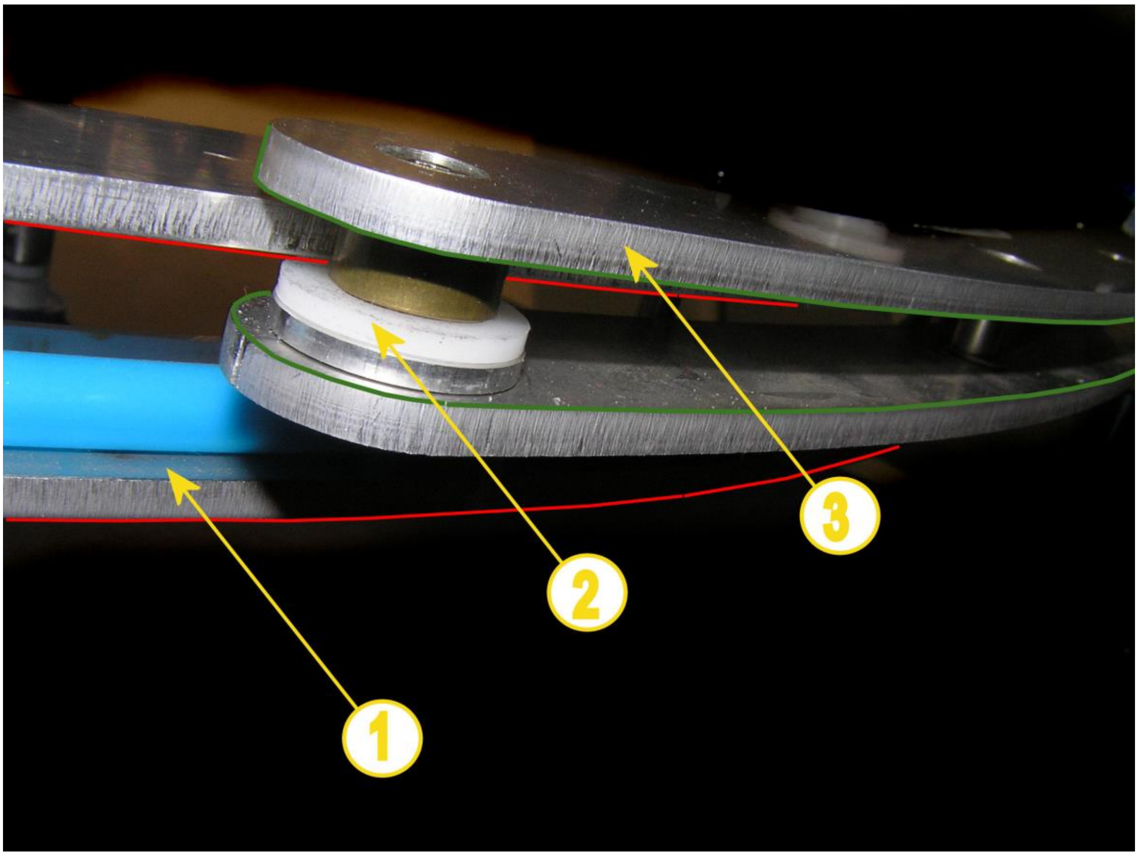

Figure 2.32: After the success of the universal sliding units, this solution was also implemented at the linear rotating unit with equal success. The image above shows some details of the rotating linear unit (3) which is equipped with the universal sliders (2) in order to slide with low friction on the ring shaped frame (1). (Source: Idaswind GmbH photo archive)

*Stepping sensor concepts*

The stepping sensors were always a concern during the development process of the robot. The initial mechanical telescopic switch sensors worked acceptably so but their limitations regarding the curved surfaces and the inherently low reliability were definite drawbacks. The improved mechanical sensors with the inductive switches were much more reliable but they were heavy and had more or less the same limitations with the old mechanical sensors when the stepping surface was strongly curved. Other mechanical sensor concepts were also designed and simulated but most of them were either structurally un-reliable or too complex and heavy.

The implementation of a completely new sensor system was examined and all the possible sensor systems were considered. The mechanical sensors were not very attractive due to reliability and complexity issues, while the composite materials of the wind turbine blades prevented the utilization of magnetic or inductive sensors. Therefore the research was focused more on the optical and ultrasonic sensor systems which seamed to be very promising for the current application. The simple and low cost optical sensors are usually equipped with a strong LED as the light source and a photosensitive surface for the recognition of the light reflection. They can measure distances with relatively good accuracy and they weight just a few grams. Their prices are low and the analog signal that they produce can be easily transformed to digital and be transmitted to the main control unit. However, after some tests it was clear that these sensors could not produce accurate measurements when they had to measure highly illuminated reflective surfaces like a white wind turbine blade during a sunny day.

Additionally the changes in the ambient illumination (e.g. short-time cloud shading) would influence the measurement of these optical sensors significantly.

Figure 2.33: Diffuse light sensor from FESTO (Source: FESTO)

Since the aforementioned sensors did not qualify for the utilization on the robot, the next step was the performance evaluation of the triangulating LASER sensors. These sensors are equipped with a strong diode LASED which sends a light beam on the blade surface. The reflection and the angle of this beam, scanned from an optical sensor gives the exact distance between the sensor with an incredible accuracy of 0.085mm and the surface via triangulating calculation. Here the reflectivity of the surface and the ambient light intensity does not influence the measurement (there is a small influence but it is insignificant) therefore the use of this kind of sensor would not be a problem. However these sensors have some very important drawbacks that cause their disqualification, such as the relatively big dimensions, the increased weight, the high electrical consumption and the very high price (around 1000€ per sensor).

Figure 2.34: High accuracy laser triangulating sensor from Balluff. (Source: Balluff GmbH)

The last sensor system that was investigated was the ultrasonic transmitter – receiver sensors. These sensors are widely used in commercial products, such as the car parking systems, where they measure distances with high accuracy. Their low cost and their commercially proven concept were some of the positive factors for the utilization of these sensors. However during the research some of their drawbacks were revealed, such as their high energy demand and the specific geometric restrictions regarding the positioning of the transmitter and the receivers of the system. Up to now it was not possible to find a proper mounting point in order to acquire precise distance measurements in all types of stepping surfaces, since the centrally mounted transmitter cannot equally excite the receivers (mounted on the outer legs) when the robot is stepping on strongly curved surface. The outcome of the whole sensor research was that the initial mechanical switch sensors were the system with the least number of problems and disadvantages, however various other designs of the ultrasonic sensors will be tested in order to find a system, which behaves properly under various conditions and surfaces.

*On-board energy source*

One of the most crucial aspects of the robot development process was the energy consumption reduction. Everything should be as lightweight as possible and at the same time as energy efficient as possible. Unfortunately the air consumption of the pneumatic cylinders and vacuum pumps was too high for on board production, therefore the robot is forced to have a physical connection with an air pressure base station, which provides pressurized air through a lightweight plastic flexible tube. Though the air connection of the robot with the base station is unavoidable, the heavy, long power and communication cable connections had to be avoided by all means.

In the communication domain, the solution was fairly simple and it was implemented in the form of wireless Bluetooth communication system. The system was integrated in the circuit board of the control system, leading to a weight increase of approx. 20gr instead of a heavy 50m long data bus cable. The power supply though was a much more complicated issue, since the energy consumption of the electronic valve unit, the control circuit and the vacuum system was as high as 600mA at 24Volts. The solution of a power cable was out of the question due to the weight of such a cable and also due to the inevitably high resistive losses of a 24V system with a 50m cable. Some sort of on-board battery system was required and after extensive research, a custom made power pack from Li-Po accumulators was designed. The low weight of these accumulators and their relatively small size enabled their placement under the electronics' compartment of the robot, in such a way that it would be possible to remove them easily and fast from the robot and recharge them. The autonomy of the robot was considered to be around 4hours with a fully charged battery pack, but further extensive battery tests have to be performed in order to check the robot's performance with this energy source.

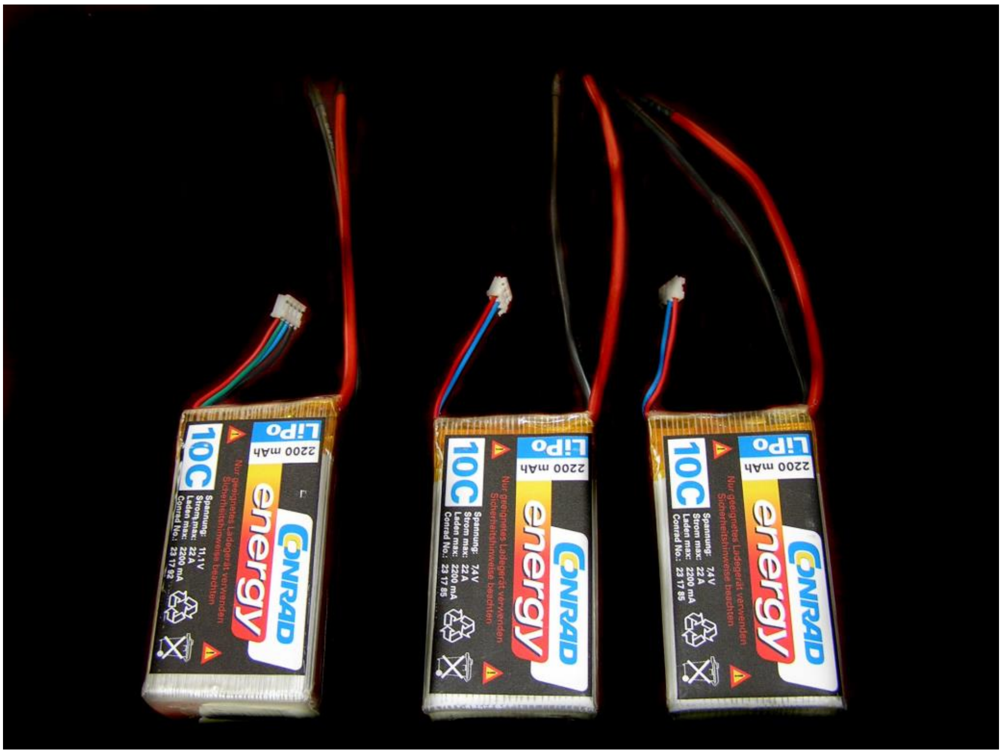

Figure 2.35: The Li-Polymer accumulators with a capacity of 2200mAh are combined in an on-board power pack. They will power the electronics and control systems of the robot for approx. 4 hours. (Source: Idaswind GmbH photo archive)

*New cable guiding*

The modification of the pneumatic cylinder positions inevitably changed the routes of many cables and air tubes, therefore new guiding systems had to be constructed. The newly developed systems were slightly more sophisticated since they were all positioned on a common cable guiding mounting frame and they were manufactured in such a way that they were able to rotate freely around several axes. The design and construction of all these parts was optimized for the in-house workshop capabilities of Idaswind GmbH and the final result was pleasing, since all the cable twisting and stacking problems of the previous systems have been solved.

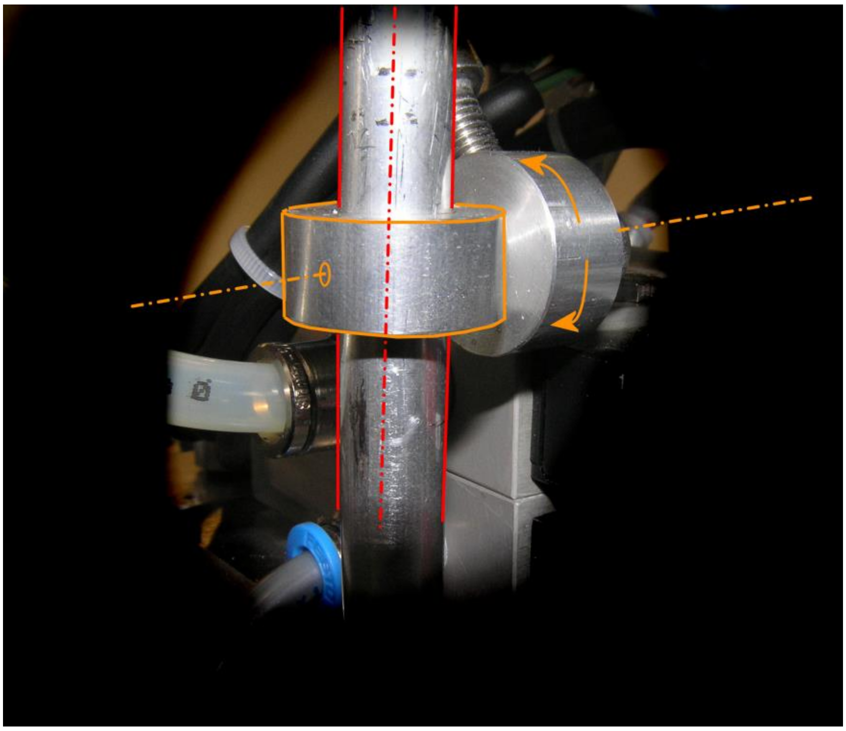

Figure 2.36: New design of an articulated cable guiding system, which permits the controlled twist and bend of the air pressure tubes and the cables. (Source: Idaswind GmbH photo archive)

*Angular magnetic sensor*

The last addition to the structure of the robot was the installation of a perimetric magnetic tape sensor at the inner side of the ring frame unit. This sensor was installed on a special plastic sensor base which was fixed at the ring frame structure with epoxy based adhesive material. This sensor sends constant input signals to the control unit in order to accurately monitor the angular position of the robot at any given time. The angular sensor combined with the linear magnetic tape will enable the robot to monitor and store the coordinates of its path and ultimately, give accurate information about the location of the investigated cracks and blade irregularities.

## 2.8 Extended lab tests (Version 3.5)

The Version 3.5 of Gecko Robot started its testing session at the in-house lab test facilities of IDASWIND and the first results were positive. The robot was slightly slower during its linear motion due to the more complicated linear stepping process (dual slider), but the speed was still sufficient for a blade scanning session within reasonable time. The control system performed also well during the edge avoidance tests and the robot was able to move along the test surface for a long time (more than 2 hours) without any fault or unexpected interruption.

During the curved surface motion tests it was unfortunately revealed the even this improved version was not able to tackle the small radii that would be found on the wind turbine blade surface. The leg arrangement did improve the situation considerably without however being able to completely eliminate the problem. Since the robot would not be able to cover the complete blade surface, a new design had to be developed in order to push the complete project to the right direction towards the accomplishment of the tasks and pre-set targets.

## 2.9 Robotic Platform Development (Version 4)

*New mechanical design*

In order to radically redesign the Gecko Robot, the design team had to start from white paper and develop a completely new robotic concept which would include all the positive aspects of the previous designs but would also be able to tackle the challenges that the previous versions failed at. The general target was a massive weight and dimension reduction, which would enable the robot to tackle the small radii of the blade. Additionally the weight reduction would enable the utilization of smaller electronics, vacuum and air pressure components therefore additionally reduce the power consumption of the robot, thus reducing the battery weight further more.

The result of the extensive CAD simulations and brainstorming lead to a new lightweight (only 4kg) small robot with all the functionality of its old predecessors but without their problems. The new robot was based on a main top unit where the outer pneumatic cylinders (for vertical motion) were rigidly mounted together with all the electronics, batteries, vacuum pumps and electronic air pressure valves. The structure of the top unit consisted of 3mm thick alloy plates fixed in distance by means of bolts and lock nuts. The two blades were extensively optimized and lasercut from a single alloy sheet. Their weight was minimized and all the non loaded and non functional areas were removed.

The construction itself acted as a 3D I-Beam due to its design thus providing enormous stiffness to the robot. That characteristic was important for the stability of the whole structure but the initial concern was related to the possibility of the structure being over-stiff thus reducing the ability of the robot to walk over curved surfaces.

The bottom unit of the robot assembly consists of an alloy slider beam build by IGUS GmbH equipped with polymer self lubricating sliders from the same company. The polymer sliders were connected together by a rectangular plate and form the sliding undercarriage on which the central vacuum cup assembly was mounted. The sliding undercarriage could slide on along the sliding beam powered by a pneumatic cylinder. This operation provided the linear motion of the robot. The central cups were mounted on a triangular alloy plate and the plate was attached to the undercarriage by means of three spring-rod connections. This kind of connection enables the robot to wobble while the central vacuum cups are secured on the blade surface. The variable angle of the robot enabled the outer cups to attach properly to the blade surface and when the attachment is complete a pneumatic cylinder locks the wobbling undercarriage in position.

The key element for the connection of the top and bottom units was the bearing assembly unit. This unit comprises a conical roller bearing mounted in a specially designed housing connected to a plastic gear. The inner part of the bearing was connected to a hollow shaft assembly which also incorporated the disk brake assembly. This kind of connection maintained the top and bottom units securely connected while it provided trouble free, low friction turning of the units. The turning process was done by means of a pneumatic cylinder equipped with a linear geared beam which interacts with the aforementioned plastic gear. The hollow bearing shaft served additionally as cable – tube guiding system and provided an optimum position for the placement of the tubing for the undercarriage connections. Topologically this position was optimal since there is no cable twisting problem due to the rotation of the bottom and top unit against each other.

The aforementioned brake disk also served as an additional security system in order to prevent the accidental rotation of the top or bottom unit. The brake was activated by a small pneumatic cylinder equipped with brake friction pads. Although this feature provided improved control over the robot it was potentially unnecessary due to the fact that the pneumatic cylinder responsible for the rotation is very powerful and can probably guarantee the trouble-free performance of the system.

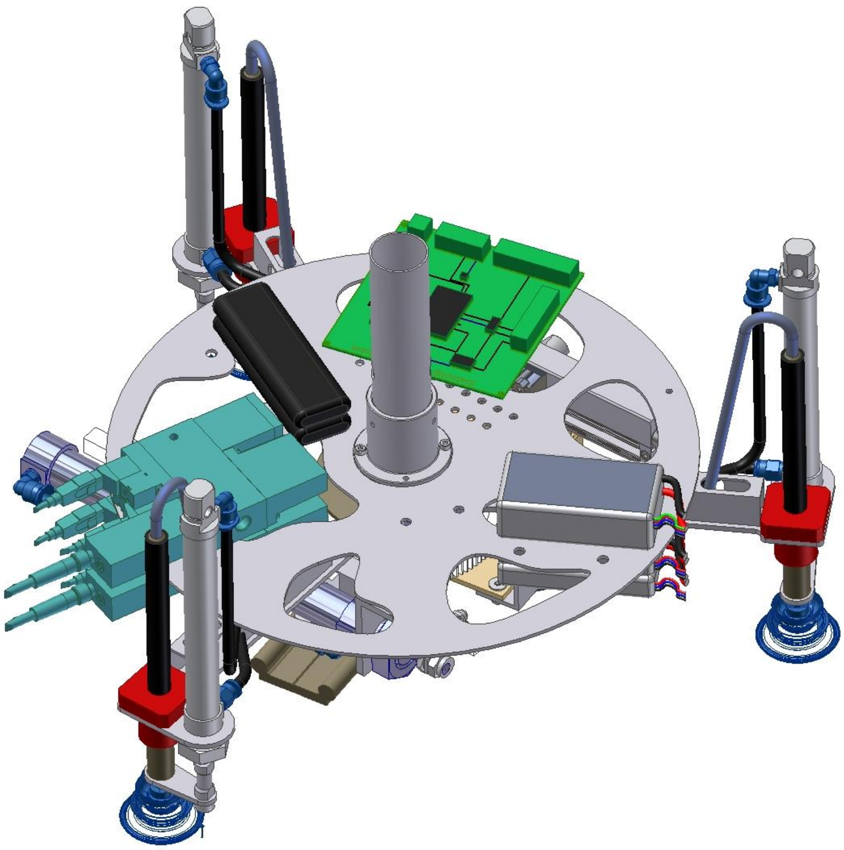

Figure 2. 37: The current version of the Gecko Robot (Version 4) was the result of complete re-design process with numerous new features and great mass and size reduction.
(Source: Idaswind GmbH photo archive)

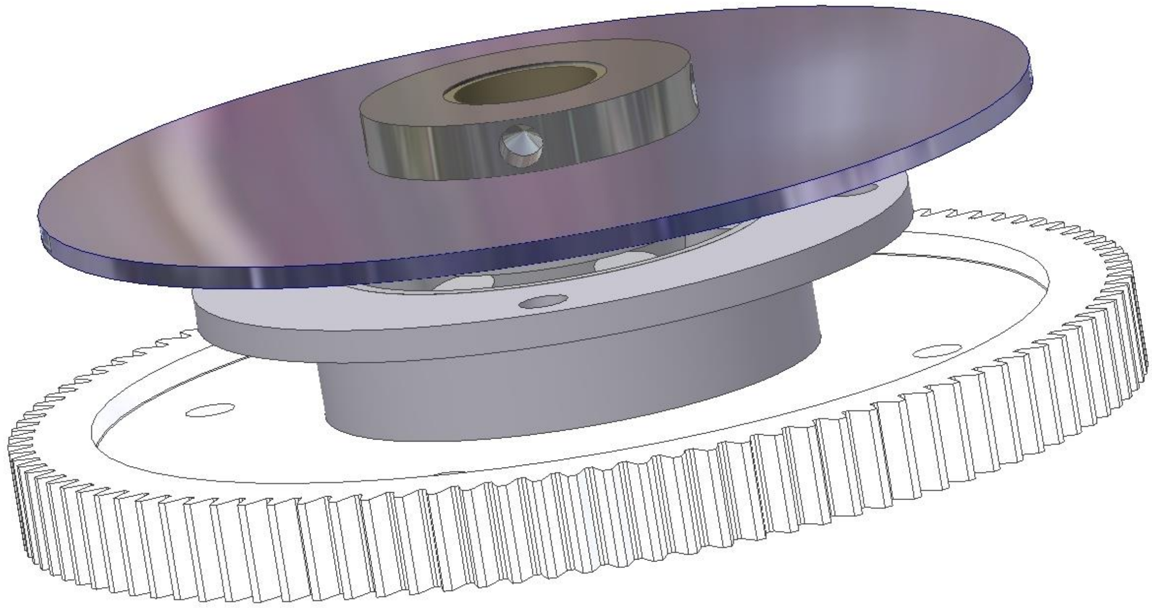

Figure 2.38: The connection of the upper and lower unit of the robot comprised a conical roller bearing in an alloy cage which was fixed to a polymer gear. The top part was fixed to the hollow shaft of the bearing unit. The disk brake prevented the false rotation of the robot during operation.
(Source: Idaswind GmbH photo archive)

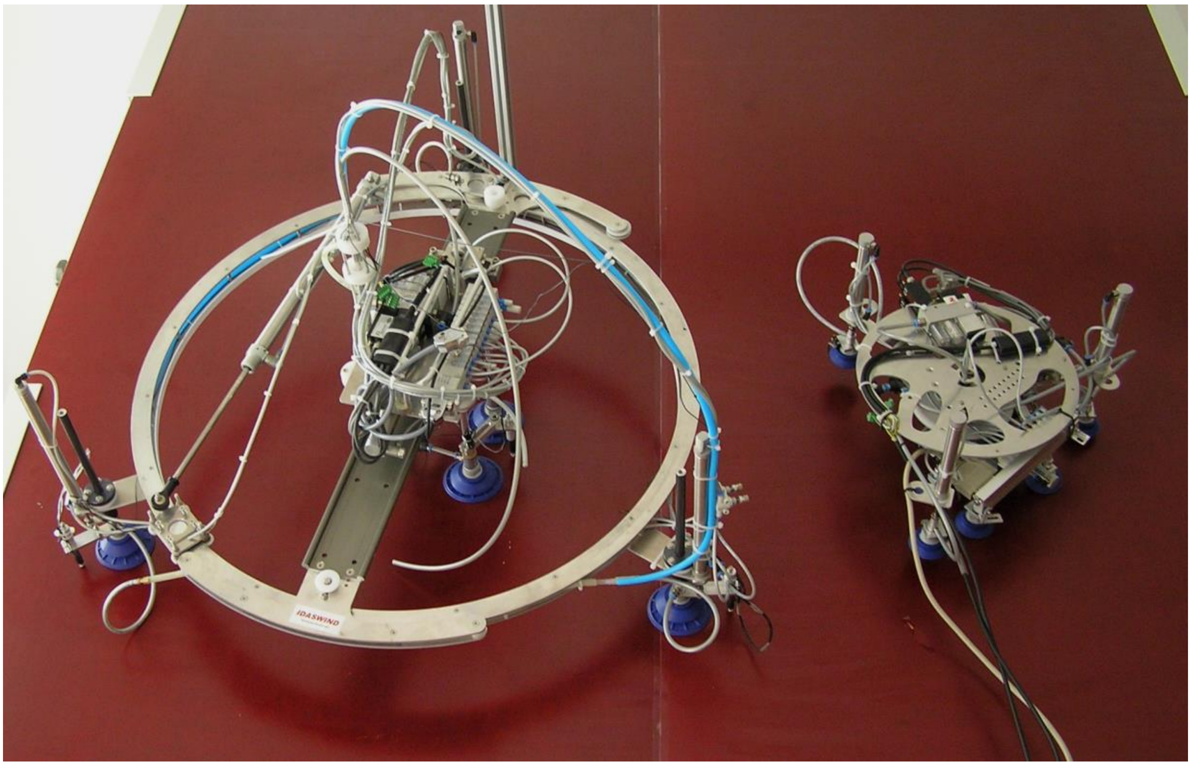

Figure 2. 39: Comparison of the version 3.5 of the Gecko robot with the current Version 4. It is obvious that the size of the latest design is reduced almost by a factor of four. Furthermore, the weight was reduced almost by a factor of five!
(Source: Idaswind GmbH photo archive)

## 2.10 Extended lab tests (Version 4)

As soon as the construction of the 4th version of Gecko robot was ready, extensive tests were conducted in order to improve the new design concerning any slight problems. The general operation of the robot was satisfactory and virtually trouble free. What was apparent was the fact that the vacuum cups of the robot should be further optimized in size and properties in order to further reduce weight (size reduction) and enable even higher flexibility in order to tackle even smaller radii of stepping surface.

New flexible cups were installed and the tests continued with much success. The robot was tested on many different surfaces with positive result, even though the rough surfaces (such as painted walls) demanded almost continuous operation of the vacuum pumps in order to maintain the connection to the wall. In addition to the new vacuum cups, the wobbling central carrier managed to bring the outer legs of the robot in such a position that good attachment to moderately curved surfaces was possible.

In general the current version of the robot performed very well on flat surfaces and quite well on curved surfaces. However when the curve radius became even smaller, the flexibility of the wobbling carrier and the vacuum cups reached its limits and the robot was at the limit of detachment. This somehow slightly limited the performance of the robot, but in general the attachment ability of the robot was considered acceptable.

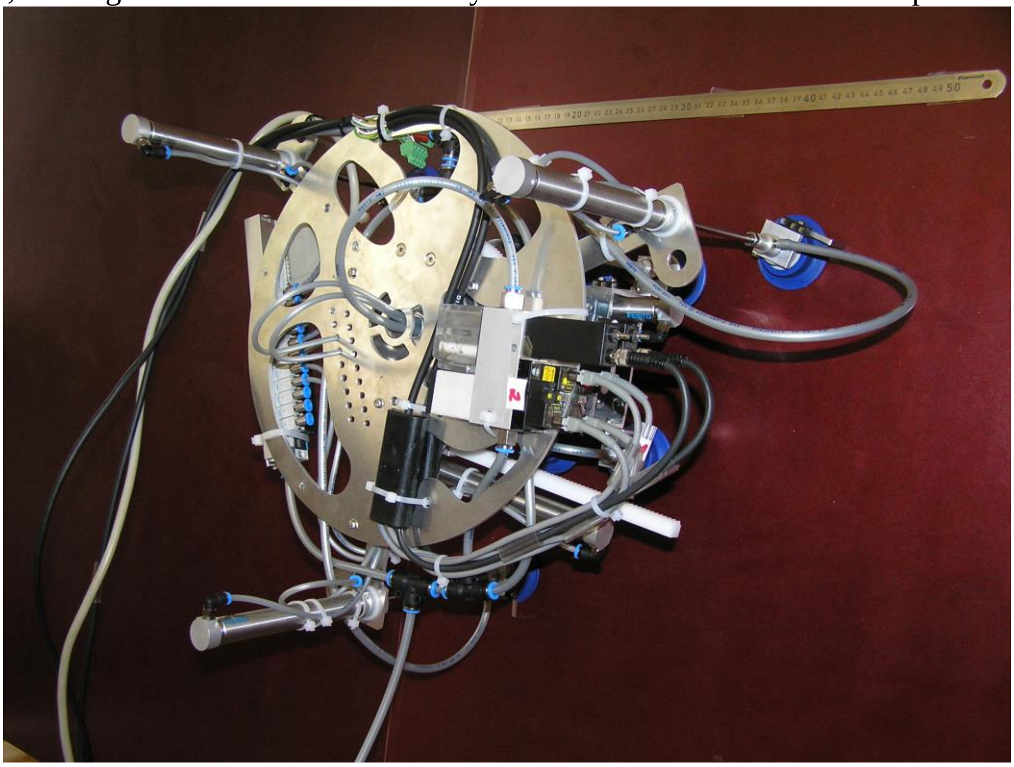

Figure 2. 40: Close view of the current version of Gecko Robot. The measuring stripe next to the robot reveals the greatly reduced dimensions of the current version (aprox. 40cm diameter) (Source: Idaswind GmbH photo archive)


Figure 2. 41: Views of the current version of the Gecko Robot, walking on various vertically oriented surfaces. The behavior of the robot was trouble free and completely satisfactory during these tests. (Source: Idaswind GmbH photo archive)

## 3. Control System

The follwing chapter describes the development of the control system of the robot, which belongs in the **Work Package (AP) 8**.

Die Steuerung des Robotersystems erfolgt mit einer für den GECKO entwickelten, vielseitig anpassbaren Mirkoprozessor Steuerungseinheit (siehe **Abb. 3.**). Sie ist als sehr kompaktes und robustes Onboardsystem auf dem Roboter integriert. The electronig hardware and the control system of the robot was developed by the company Naventics GmbH under the instructions of IDASWIND GmbH.

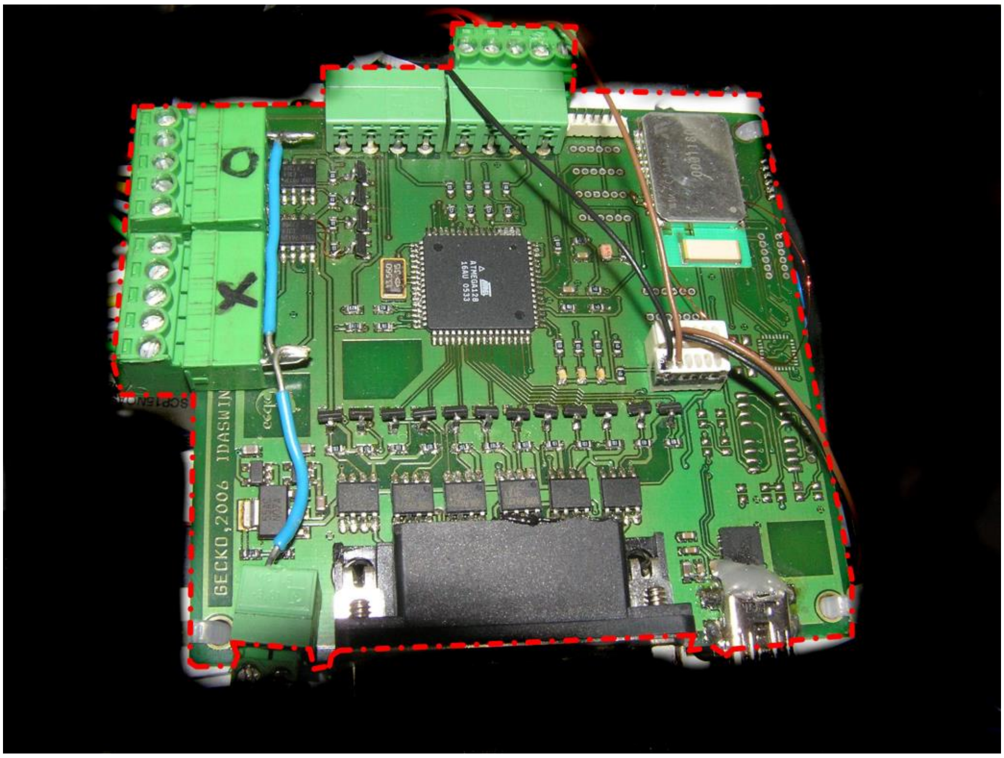

Abb. 3.1: Onboard Steuerungseinheit

Die Einheit verfügt über 20 digitale und fünf analoge Eingänge sowie 10 digitale Ausgänge.
Mit Hilfe dieser Steuerungseinheit wird die Kommunikation via WLAN zum Steuerungsrechner (z.B. Laptop) sowie zu den elektronischen Luftdruckventilen hergestellt.
Als Graphical User Interface (GUI) wurde eine eigenständige Oberfläche programmiert, die sowohl den manuellen (siehe **Fehler! Verweisquelle konnte nicht gefunden werden.**), als auch den vollkommen automatischen Betrieb des Roboters (siehe **Abb. 3.3**) mit selbstständiger Rotorblattranderkennung ermöglicht.

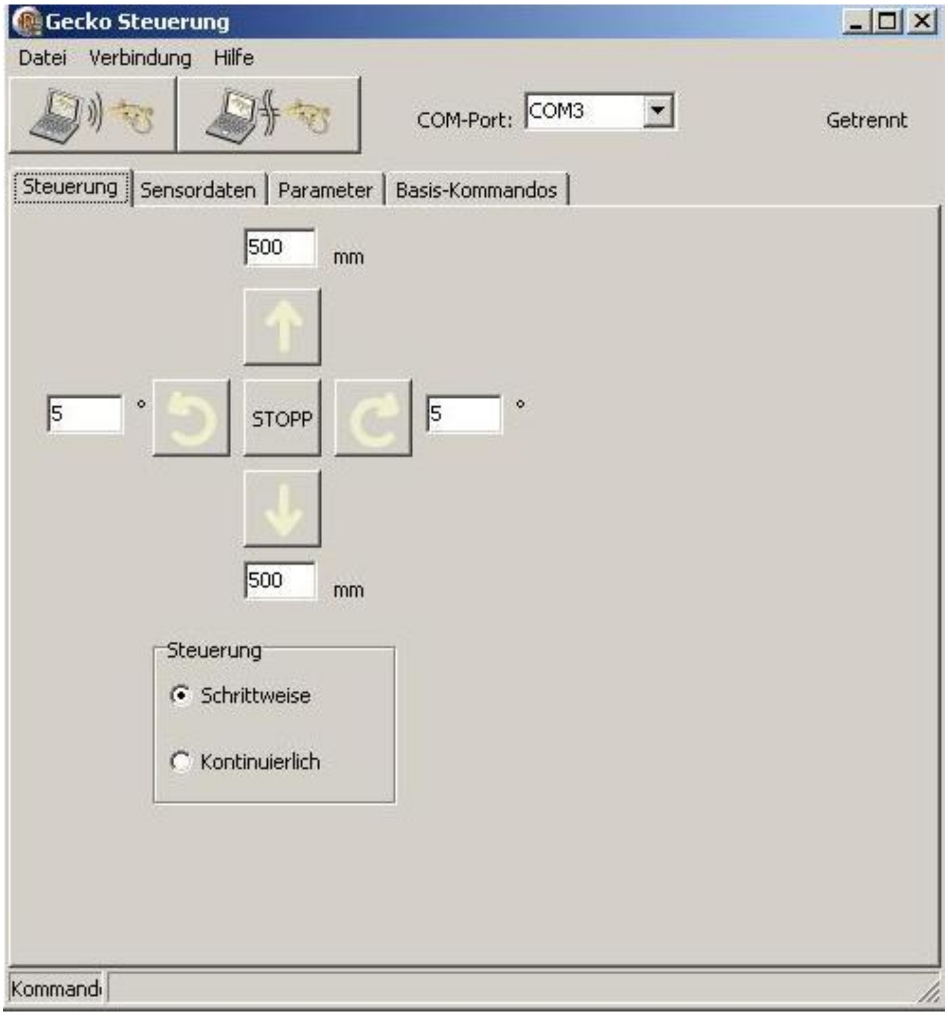

Abb. 3.2: GUI (manueller Betrieb)

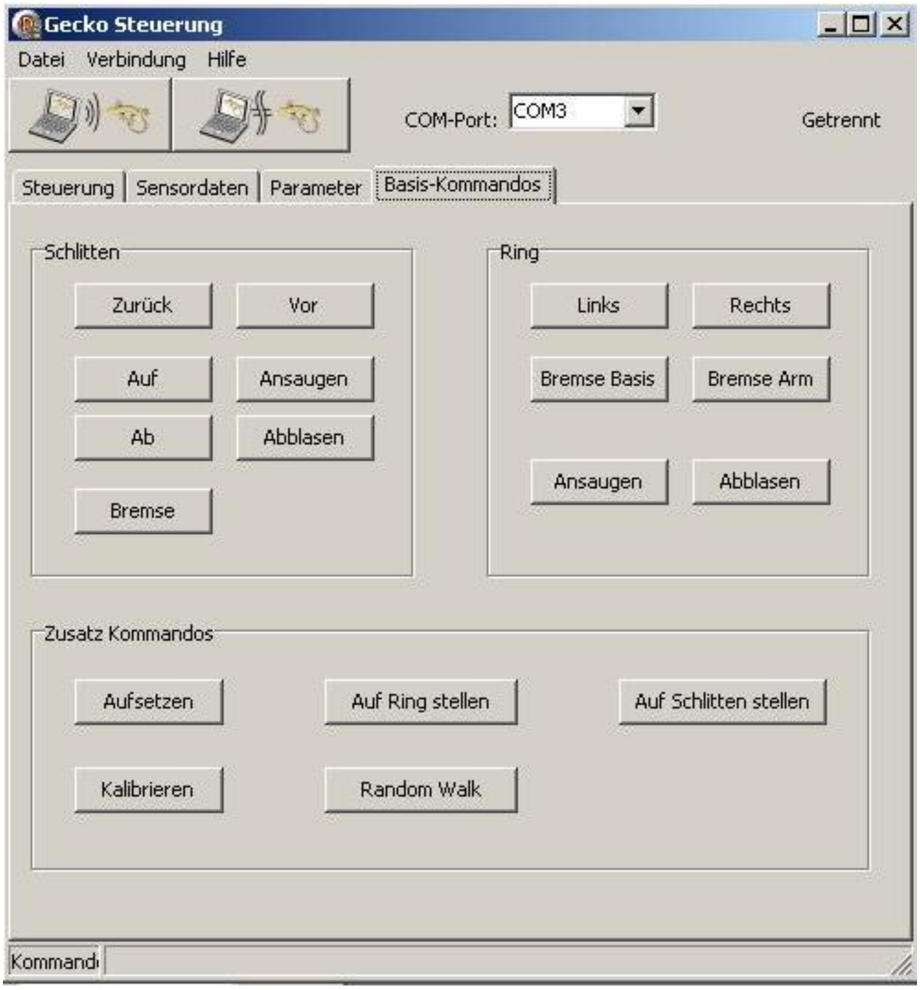

Abb. 3.3: GUI (automatischer Betrieb)

Um das Verhalten des Roboters während des Test-, aber auch im späteren Servicebetrieb an die jeweiligen Gegebenheiten anpassen zu können, stellt das GUI eine einfache Schnittstelle für die Eingabe der Steuerungsparameter zur Verfügung (siehe **Abb.** ).

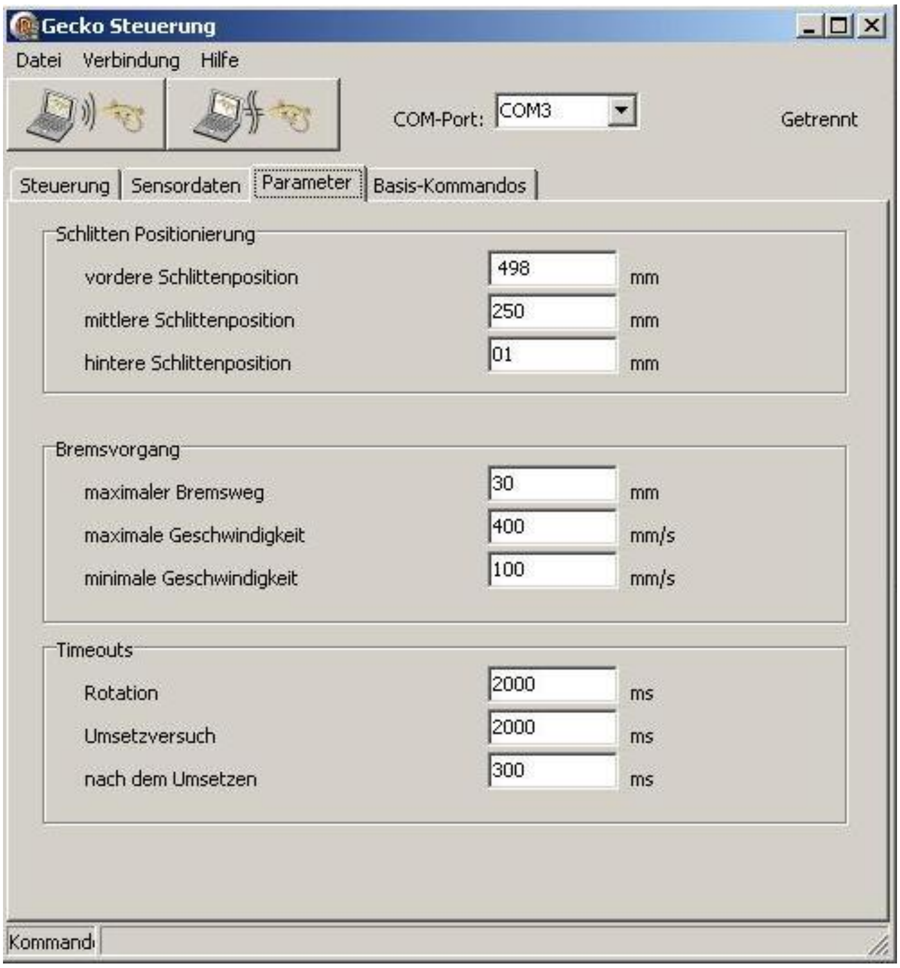


Abb. 3.4: GUI (Steuerungsparameter)

Bei der Entwicklung der Steuerungshardware und -Software wurde großen Wert auf Anpassungsfähigkeit gelegt. So wurden z.B. die Software Schnittstellen möglichst weit gefasst und durch die hohe Anzahl von Hardwareeingänge und -Ausgänge kann eine Vielzahl weiteren Signale erfasst und weitergeleitet werden.

## 4. Security System

The following chapter present the development of the Security System of the robot and corresponds to the **Working Package (AP) 5** and **6** of the project plan.

### 4.1 Existence or not?

The robotic platform described at the previous section in designed especially for inspection tasks of installed wind turbine blades. The design of the robot ensures the proper and secure attachment of the robot on the wind turbine blade surface and both the mechanical construction and the control system have special characteristics and security functions, which minimize the risk of detachment of the robot from the blade. Would it be possible however to operate such a robotic system on a wind turbine blade without any means of physical security system? In theory it would be possible, provided that all the on board security characteristics of the robot operate properly. Extended tests on various surfaces showed that the mechanical design and the control system manage to keep the robot attached to the blade surface under any tested incident, which means that the robot could run without the existence of a security system. However if for any reason the detachment of the robot would occur, the working level is so high (50m-100m) that the complete destruction of the robot would be certain.

### 4.2 Security system details

Many different security system ideas were sketched and roughly calculated during the development process, however the most feasible and economic solution was the traditional safety cord system. Unfortunately this solution restricted the operational envelope of the robot to the vertical area under the security system, which means that only the vertical blade of the turbine would be able to be scanned and after its examination the rotor should turn until the next blade reached the vertical position. This security system should combine many different characteristics in order to be able to function without any problem at any given wind turbine inspection. The most important issue was the fact that the security system should be portable and should also be able to enter the wind turbine nacelle or even the rotor nose cone by the standard access hatches. Secondly, the security system should be able to control a possible fall of the robot in such a way that the mechanical and electrical components of the robot would not be subjected to high stresses and shocks. At the same time the security control system should be able to tighten constantly the security cord (or steel wire) while the robot is moving on the blade in order to prevent an extended fall of the robot, which would lead in extended acceleration (and deceleration) during the falling and securing process.

The main concept of the security system involved a controllable cable drum and a brake mechanics. However there were some crucial points that complicated the initial solution. The fact that the 1mm diameter steel security cable should be winded on the drum together with the 10mm diameter flexible plastic tube arose some problems regarding the attachment method of the tube to the steel cable, as well as the inevitable increase on the dimensions of the winch drum. The other key point during the development of the security system was the cable tensioning function which dictated the use of some sort of tension sensor for the cable. The main difficulties regarding the tension sensor selection process were caused from the widely varying operation characteristics of the robot. More specifically, the incremental linear motion was rapid and most of the tension sensors would either misidentify it as falling (when the robot moves away from the security system and the cable tightens) or the rapid loosening of the cable would 'confuse' the sensor and cause problems to the tightening system. Therefore the tension sensor system should be able to work within large range of applied forces and at the same time enable the incremental motion of the robot.

Unfortunately all the available commercial systems were either not able to fulfill the abovementioned requirements or were not produced in the desired small physical dimensions. The next obvious step was the development of a custom made security system designed and built according to the current specific demands of the application. In the domain of tension sensor and fall damping an innovative solution was developed, which combined the low cost production with multi-functionality and low weight. The system is based on a triangular pulley arrangement with two fixed pulley and a floating $3^{rd}$ pulley. The $3^{rd}$ pulley is fixed to the piston of a pneumatic cylinder and its movement is tracked by an inductive motion sensor. The cable attached to the air tube enters the security base and is guided around the three pulleys in such a way that any cable tension would cause a coaxial force to the piston of the pneumatic cylinder. After the pulleys, the cable and the tube are winded on the rotating drum via a winding guide.

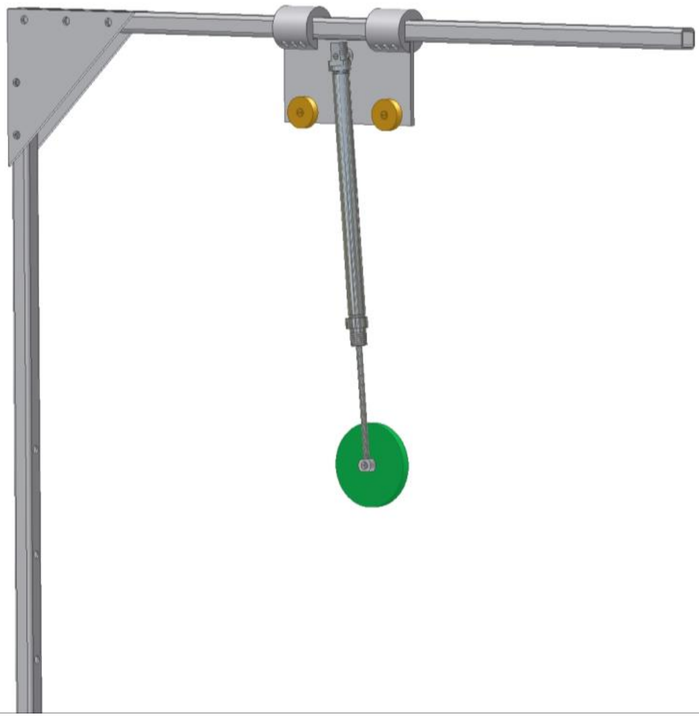

Figure 4. 1: The initial concept design for the robot security system. Two small side pulleys guide the cable and the big (green) pulley acts as a tension-damping component.
(Source: Idaswind GmbH photo archive)

This solution proved to be ingenious as it combines many functions with the least amount of components. More specifically, the system could work on a passive manner with the pneumatic cylinder being filled with air of constant pressure and act as a cable tensioner and fall damper at the same time. In this case a given displacement of the middle pulley (and the piston of the pneumatic cylinder) would be translated to a displacement of the double length of the cable thus enabling a significant rapid tension variation even before the control unit turns the cable drum in order to compensate the momentary imbalance caused by a failed step of the robot. The other possibility would be a much more sophisticated active damping security system, where the control system of the security unit enters into the wireless communication process of the robot and the base station and pre-defines the tension of the cable according to the command which the robot is about to execute. In this way the cable tensioning would be very precise and the security system would be able to react instantly without the need of a physical input from the security cable.

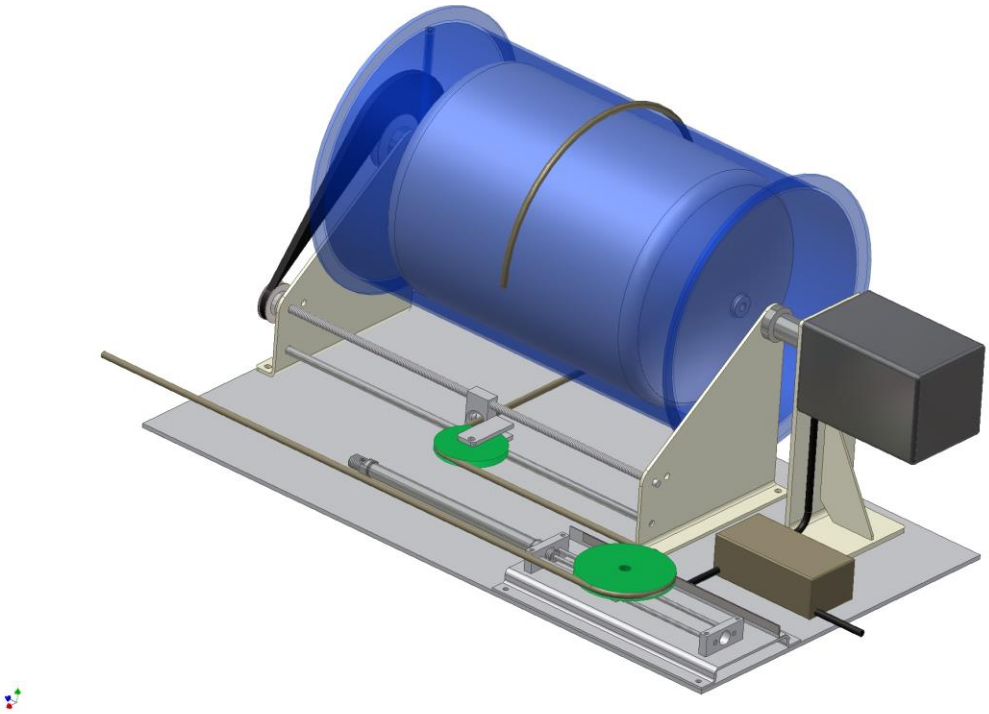

Figure 4. 2: The initial proposal for the cable drum winch and the pneumatic tension-damping system. (Source: Idaswind GmbH photo archive)

Since the general technical solution for the security system was finally decided, the design process was accelerated and the focus was concentrated on the optimization of the whole structure. The cable drum was elongated in order to enable a single layer winding of the cable which would simplify the damping control process and a powerful electric step motor was selected for the rotation of the cable drum. The choice for a step motor instead of a much cheaper DC or AC motor was due to the beneficial characteristics of the step motors in terms of starting torque, control possibilities, precise angular control and high electric brake power. The construction of the cable drum had to be custom made since the winded air pressure tube should be able to come out of the drum and reach the air compressor base station (on the ground). For this purpose the bearing mounted cable drum was equipped with hollow shafts in order to allow the installation of a rotating air tube connection. Additionally the hollow inner volume of the cable drum was hosting a commercial high pressure air tank, which functioned as a middle buffer tank between the main air compressor base and the robot. The function behind this idea had to do with the elimination of the delay and pressure fluctuation of the system from the spot of pressure generation (air compressor base) until the robot when the air had to pass through 150m of flexible air tube. Therefore the existence of the buffer tank would damp the pressure fluctuations and would also serve as short term pressure storage in case of a failure of the main compressor system.

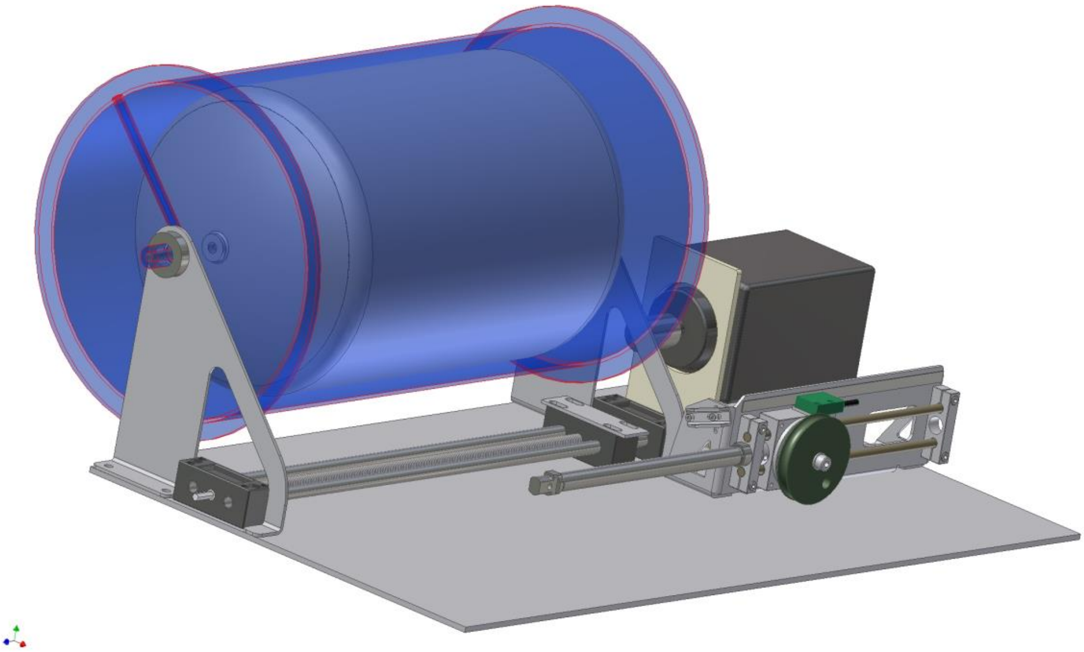

Figure 4. 3: A newer design of the damping system equipped with commercial components and designed for space and cost optimization. Note that the designing process is yet unfinished thus many components are missing. (Source: Idaswind GmbH photo archive)

Due to the continuous development and optimization process of each one of the units and individual parts of the project, it often occurs that a single unit was redesigned several times. The following images show the last version of the security system unit, after the last modifications. The spatial efficiency is increased due to the new compact configuration of the cable tensioning unit and the utilization of a small sized step motor. The cable tension monitoring is performed as usual by the sliding pulley unit and the signal of the motion sensor of the sliding unit is sent to the control unit in order to perform the step motor control. The step motor engages a gear with a transmission ration of approx. 1:5 and it was able to control the rotation of the cable drum (winding and unwinding the cable-tube). The uniform winding operation was performed by a winding slider which moved with a screw with trapezoidal thread. The aforementioned screw was turning with the proper speed due to the implementation of a synchronization pulley – belt transmission, driven by the cable drum. The secure stopping position of the drum is assured by the addition of two lightweight pneumatic brakes, which engage directly the side plates of the cable drum in order to provide sufficient braking power to the system.

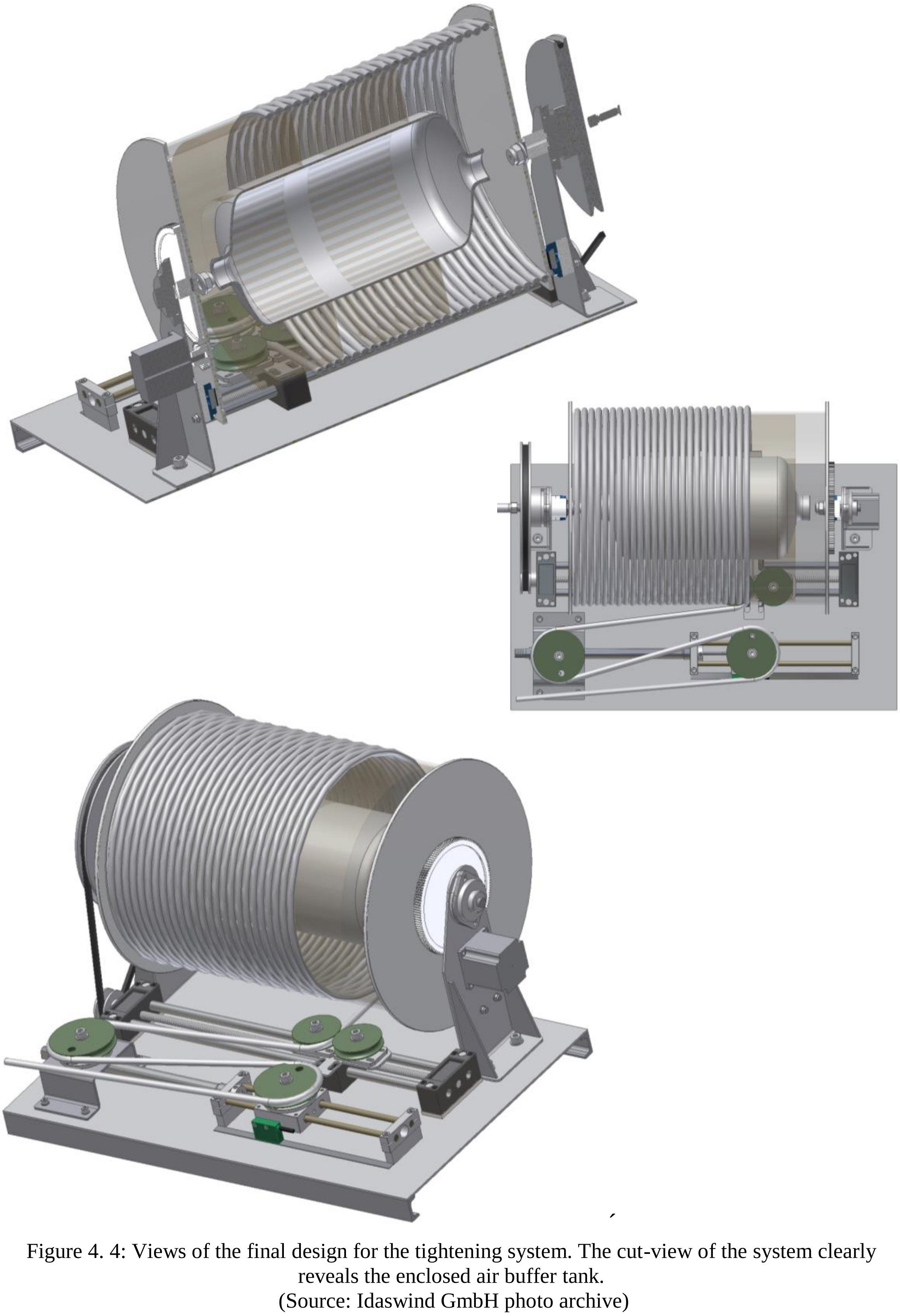

Figure 4. 4: Views of the final design for the tightening system. The cut-view of the system clearly reveals the enclosed air buffer tank.
(Source: Idaswind GmbH photo archive)

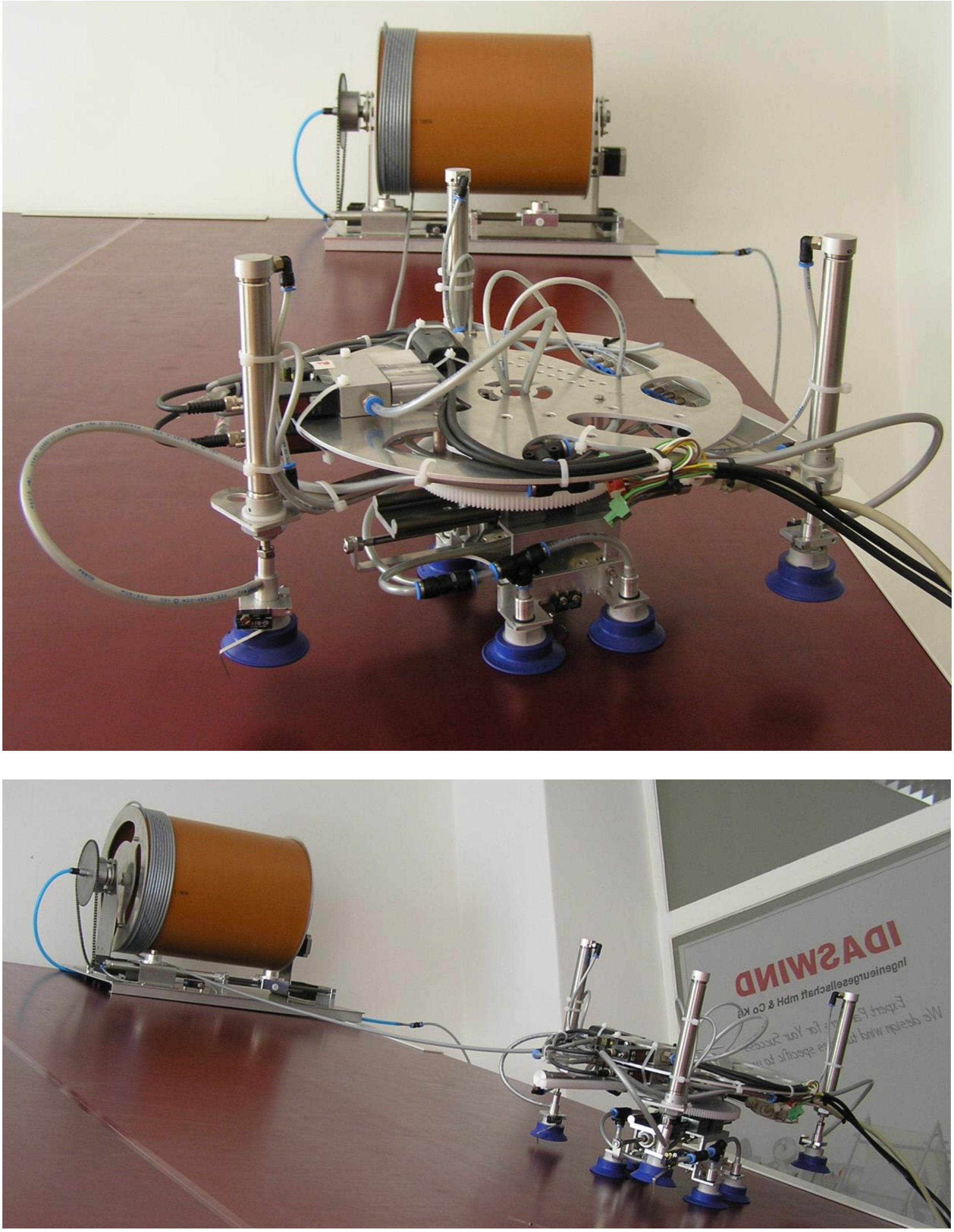

Figure 4. 5: Photos during the initial tensioning system tests with the current version of Gecko Robot.
(Source: Idaswind GmbH photo archive)

## 5. Crack recognition system

The following chapter presents the developments in the field of blade surface scanning and infrared thermography. These tasks represent the **Working Packages (AP) 11, 12, 13** and **14.**

### 5.1 Ergebnisse (?)

Für die vom Robotersystem aus erfolgende Bilddatenaufnahme wurde ein Konzept entwickelt und prototypisch umgesetzt.

*Randbedingungen und Vorgaben*

Um den Zusammenhang zwischen optischer Auflösung, Bilddatenmenge und erkennbarer Fehlergröße  abschätzen zu können, wurden folgende Randbedingungen formuliert:

- Die zu scannende Oberfläche beträgt etwa 100 m².
- Ein Teilbildausschnitt umfasst eine Fläche von etwa 18 cm x 13 cm.
- Die fehlerfreie Oberfläche ist annähernd homogen, eine Teilbildfläche umfasst mehr fehlerfreie als fehlerhafte Bereiche, zu erkennende Merkmale unterscheiden sich in der Helligkeit ausreichend von der Oberfläche.
- Eine Fehler (z.B. Riss) hat eine Ausdehnung von mindestens 3 Pixel (Breite und Höhe).
- Farbinformationen werden nicht benötigt.
- Die optische Achse der Kamera steht annähernd senkrecht zur Oberfläche bei einem festen Arbeitsabstand von ca. 15 cm, Krümmungen der Oberfläche sind klein gegenüber dem Abstand.
- Eine diffuse Beleuchtung (Tageslicht oder LED-Strahler) reicht aus.
- Die Bilddatenmenge sollte die Kapazität einer DVD (4.5 GB) nicht überschreiten.
- Die erforderliche Hardware (Kamera, Beleuchtung, Datenverbindung, Spannungsversorgung) wird mit zusätzlichen Alu-Profilen fest auf dem Gecko-Rahmen montiert.

*Gerätekonfiguration*

Als Kamera wurde eine digitale Mini-Kamera des Typs Guppy F80C (Hersteller Fa. AVT) mit IEEE1394-Schnittstelle „FireWire“ ausgewählt. Die Spannungsversorgung erfolgt über das FireWire-Interface. Die Auflösung beträgt 1032 x 778 Pixel (s/w oder Farbe), alle wichtigen Funktionen (z.B. Bildgröße, -format, Shutter) sind über die bidirektionale Schnittstelle steuerbar.

Wegen des geringen Arbeitsabstands und des vergleichsweise großen Bildfeldes kommt als Optik nur ein kompaktes fokussierbares

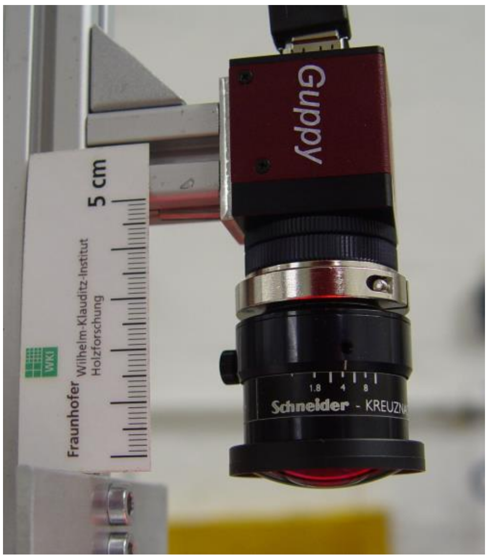

Abb. 5.1: Kamera mit Präzisionsobjektiv

Präzisionsobjektiv (SKR KMP-IR Cinegon, Brennweite 4,8 mm/F1.8, Bildwinkel ca. 45°, Schneider – Bad Kreuznach) in Frage.

Für die Beleuchtung wird ein LED-Auflicht (Typ LFR-200-R, Hersteller CCS) vorgesehen. Es besteht aus einer runden Scheibe (Durchmesser 200 mm, mit 70 mm großer Öffnung für die Kamera) und erzeugt sehr diffuses rotes Licht (Wellenlänge ca. 660 nm). Damit ist es möglich, entweder durch ein Farbfilter vor der Kamera oder durch Auswahl des Rot-Kanals bei der Bildauswertung Fremdlicht zumindest teilweise zu unterdrücken. Zur Versorgung ist ein Vorschaltgerät erforderlich, das 12 V Eingangsspannung liefert. Alternativ dazu wäre baugleich auch ein Weißlicht-LED-Modul erhältlich, das jedoch eine höhere Eingangsspannung und damit einen zweiten Akku (s.u.) erfordert hätte. Ein anderer Aufbau (Schräglicht erzeugende LED-Balken, parallel angeordnet zu den vier Rändern des Bildfeldes) wurde ebenfalls zurückgestellt, weil mehr Mechanik für die Justierung erforderlich gewesen wäre.

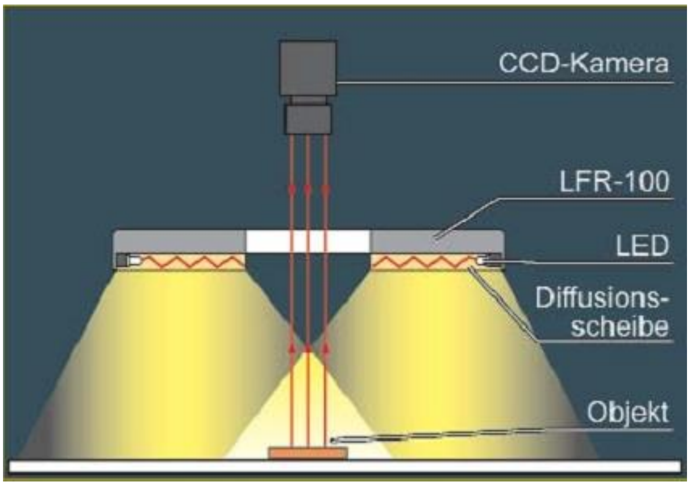

Abb. 5.2: Schema der Kombination Kamera/Beleuchtung

Als Spannungsversorgung für Beleuchtung mit Vorschaltgerät und Lichtleiter-Umsetzer mit Kamera genügt ein handelsüblicher Lithium-Ionen-Notebook-Akku (Typ „Connect“, Anbieter Fa. Accu-Profi) mit einer Ausgangsspannung von 16 … 19 V und einer Kapazität von 7 Ah aus, womit eine Betriebsdauer von mindestens 3 h (geschätzt) realisierbar erscheint. Die Spannung reicht auch noch zur Speisung des Vorschaltgerätes für die Beleuchtung aus.
Für eine Beleuchtung mit Weißlicht-LEDs wäre allerdings ein zweiter Akku erforderlich. Die Akkus (Masse pro Stück ohne Halterung ca. 800 g) können eingespart werden, wenn zusätzlich zur sowieso erforderlichen Versorgung der Gecko-Steuerung noch eine zweite Versorgungsspannung zugeführt wird.
Die bidirektionale Datenverbindung zwischen Kamera und Rechner entspricht dem Standard IEEE 1394 und kann auf verschiedene Arten realisiert werden:

- Mit einem handelsüblichen 6poligen FireWire-Kabel, erhältlich in Längen bis zu 5 m.
- Mit einer nahezu beliebig langen LWL-Strecke, für die an der Kamera und am Rechner jeweils ein Umsetzer (OpticLink 1394-Lcset, Hersteller Arvoo) erforderlich sind.


Abb. 5.3: verlegbares Lichtleiterkabel

Kameraseitig benötigt der Umsetzer eine Versorgungsspannung zwischen 8 V und 40 V, speist damit aber auch die Kamera selbst. Für Laborversuche mit LWL-Strecke genügt ein einfaches Patch-Lichtleiterkabel, für eine Messung vor Ort wäre ein ummanteltes Verlegekabel mit einer Masse von 100 g/m erforderlich.

Alle Elemente für Bildaufnahme und Beleuchtung wurden auf dem Rahmen des Gecko mit leichten Alu-Profilen (Hersteller: Item) montiert (vgl. Abb.4). Die zusätzlich angebrachte Masse betrug ca. 4000 g.

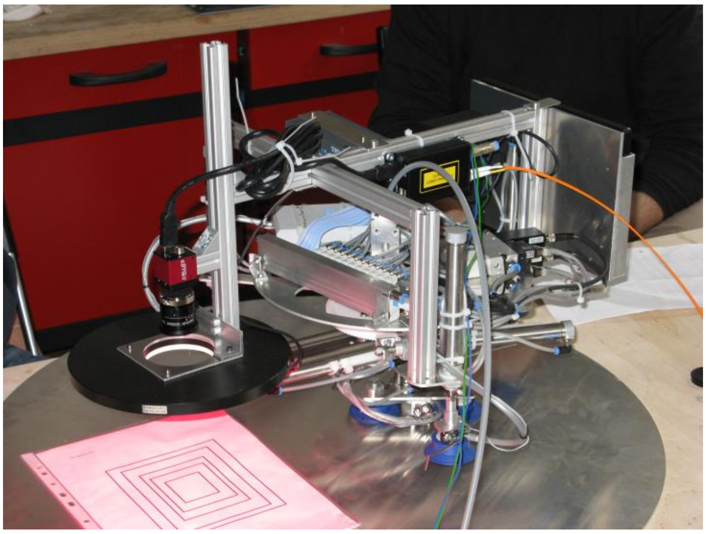

Abb. 5.4: Gesamtaufbau des Gecko
mit Kamera, Beleuchtung, Datenverbindung, Akku

*Abschätzung des Bilddatenvolumens*

Die Menge der zu verarbeitenden Bilddaten pro Rotorblatt lässt sich bei folgendem Szenario wie folgt abschätzen:

- Größe der Oberflächenausschnitte ca. 18 cm x 13 cm
- Auflösung mit Kamera „Guppy“: 1 Pixel entspricht ca. 0,17 mm x 0,17 mm
- Bei 100 m² Oberfläche ergeben sich ca. 4300 Kamerapositionen, d.h. 4300 Bilder (ohne Überlappung)
- monochrome Bilder, Größe 1032 x 778, unkomprimiert
- Bilddatenvolumen ca. 3500 MByte

Bei dieser Auflösung und Oberfläche werden kleine Objekte (z.B. Risse) mit ausreichendem Kontrast zur fehlerfreien Umgebung ab einem Durchmesser von ca. 0,6 mm hinreichend sicher erkannt. Das Datenvolumen, mit dem eine Rotorblattoberfläche vollständig dokumentiert ist, kann noch auf einer DVD gespeichert und archiviert werden. Es würde sich drastisch reduzieren, wenn die Bilder in komprimiertem Format (z.B. JPEG) und/oder von vornherein nur Bilder mit erkannten Objekten gespeichert werden. Um zu beurteilen, wie weit das Datenvolumen durch solche Verfahren verringert werden kann, müssten jedoch zunächst Erfahrungen mit realen Datensätzen gesammelt werden.

*Nachbearbeitung der Bilddaten*

Die Einzelbilder, die von der Kamera aufgenommen und zunächst im Rechner abgelegt werden, müssen automatisch vorverarbeitet werden, bevor sie gesichtet und archiviert werden können. Dazu sind folgende Schritte erforderlich:

- Shadingkorrektur, Helligkeitsausgleich (Abgleich der Helligkeitsverteilung im Einzelbild entsprechend den lokalen Inhomogenitäten durch die Beleuchtung, Ausgleich von Drift der Beleuchtung)
- Auskopplung des Rot-Kanals (wenn die o.g. Beleuchtung eingesetzt wird)
- Korrektur der geometrischen Verzeichnung durch das Objektiv
- Fehlererkennung und –markierung (Detektion dunkler Objekte durch einfache Grauwertschwelle, Vermessung, Markierung des umschreibenden Rechtecks)

Diese Funktionen wurden in der Software „RoBlSurf“ realisiert. Sie kann noch um die Zuordnung der Fehler zu realen Koordinaten und ggf. die Erstellung einer Fehlerliste erweitert werden.

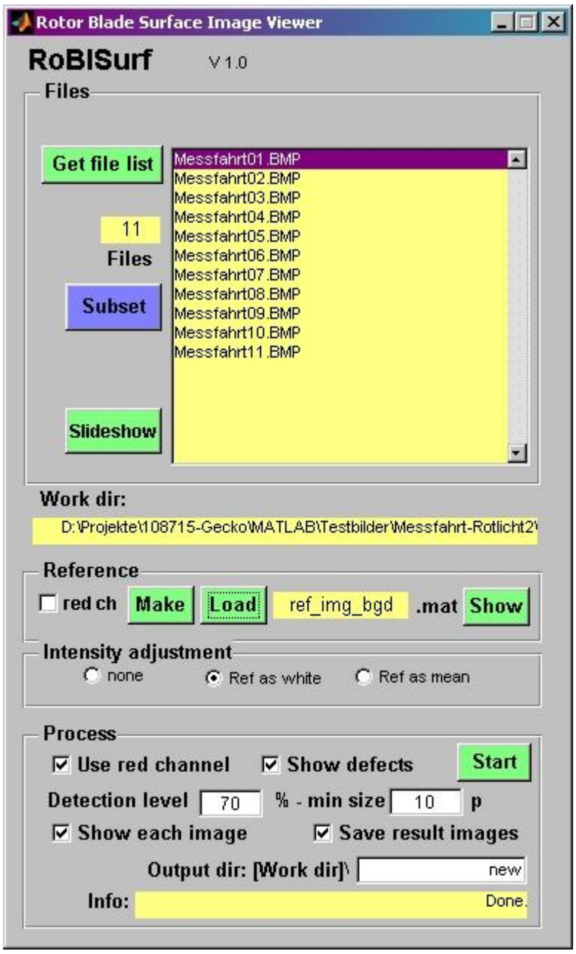


Abb. 5.5: Bedieneroberfläche der Software zur Nachbearbeitung der Bilddaten

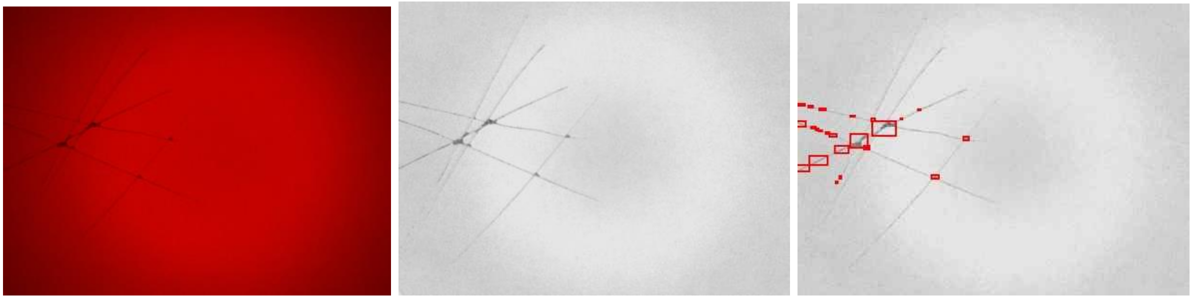

Abb. 5.6: Verarbeitungsschritte
Originalbild – nach Helligkeitsausgleich – mit Fehlermarkierung

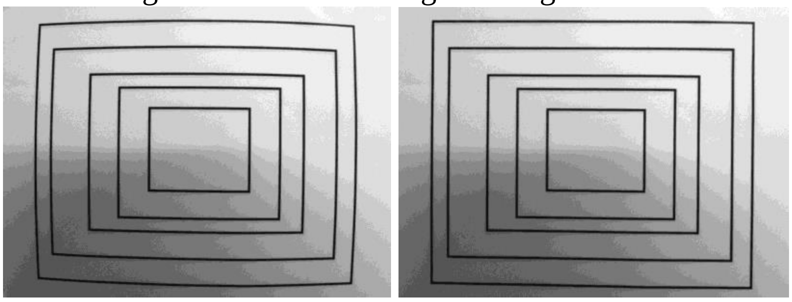

Abb. 5.7: Verarbeitungsschritte
Originalbild – nach geometrischer Entzerrung

Ein weiterer Arbeitsgang wäre erforderlich, um ein „Panorama“-Bild der Blattoberfläche zu erstellen und darin auf Basis der numerischen Oberflächenkoordinaten navigieren zu können. Dazu können bekannte Verfahren (Stitching) eingesetzt werden, mit denen Teilbilder anhand überlagernder Bildbereiche zu größeren Bildern zusammengefasst werden können, wenn diese Bildbereiche ausreichend unterscheidbare Strukturen aufweisen. Da ein Bild einer Blattoberfläche nicht mit voller Auflösung als Bilddatei gehandhabt werden kann, muss ein Verfahren angewandt werden, mit dem die Auflösung skaliert und aus der Bildserie jeweils anhand der Blattkoordinaten die darzustellenden Einzelbilder bestimmt und dargestellt werden. Diese Aufgabe kann jedoch erst konzipiert werden, wenn ein Koordinatensystem für die Blattoberfläche definiert und eine Zuordnung der Kameraposition zum Einzelbild möglich ist.

*Bisherige Testläufe*

Einige Messfahrten (vgl. Abb. 6) auf einer ebenen, hell lackierten und mit Kratzern versehenen Testoberfläche verliefen erfolgreich. Die durch die Kombination aus Kamera, Optik und Beleuchtung gelieferte Bildqualität reicht für eine Weiterverarbeitung der Bilddaten aus.

*Offene Probleme*

Bisher offen sind folgende Fragen:

- Die Tragkraft des Roboters reicht nicht für Testläufe mit den zur Bildaufnahme installierten Komponenten aus. Um Gewicht einzusparen, könnte der Akku entfallen.

- Bei der Steuerung des Roboters besteht bisher keine Möglichkeit, eine Zielposition numerisch vorzugeben.
- Die Kameraposition (Länge ab Blattwurzel bzw. Kante, Drehlage) müsste bekannt sein, ein Konzept für die Kartierung eines Rotorblattes ist zu erstellen.
- Die Kamera muss bei der Bildaufnahme getriggert werden, d.h. von der Gecko-Steuerung muss ein Signal bereitgestellt werden, wenn die Kamera vibrationsfrei in Position ist.

*Planung und Ausblick*

Vorgesehen sind bis zum Ende der Projektlaufzeit:

- Ein Testlauf mit reduziertem Gewicht (d.h. Gecko nur mit Kamera, Beleuchtung durch Tageslicht, elektrische Versorgung über Kabel) an einem Rotorblattsegment
- Versuche mit einer Thermographiekamera

## 6. Positioning

The following chapter describes the development steps of the robot positioning system, as well as the image stitching software development. These development steps correspond to project **Working Package (AP) 10**.

### 6.1 Initial Approach

The existence of a precise positioning system of the robot was considered of very high importance since the identification of failures and imperfections on the blade surface would be useless without the registration of their precise location. The initial design approach included a passive positioning system which registered the positions of the moving parts of the robot. Therefore by utilizing the already installed position sensors for the robot's motion control it was possible to precisely calculate the position of the robot on the blade surface. This concept however did not function properly when it was tested at the actual robot. The problem was related to the reduced stiffness of the main structure of the robot which enabled small relative movements between the individual parts thus compromising the positioning accuracy.

During the tests of the passive positioning system at the test lab facilities of Idaswind GmbH, the reduced stiffness of the robot's structure caused a position deviation of 8mm for every meter of linear travel. This kind of deviation would translate to roughly 400mm position deviation for a 50m linear travel (typical blade length of a modern large wind turbine). Consequently a position deviation in this range is considered unacceptable as a defect locating system therefore a different system had to be developed.

### 6.2 Final Approach

After considerable investigation it was decided that the most accurate and reliable positioning system would be an indirect positioning by precisely connecting all the images of the blade surface, taken by the robot. In this fashion, a complete synthetic image of the blade surface would be created (comprising large number of individual images of identical size). During the manual post-inspection the inspector would have the ability to check the individual images individually and locate the exact position of the defects by means of virtual software coordinates.

One issue however that posed a serious obstacle was the virtually inexistent visual contrast of the images from the blade surface. Since the blades always have a smooth white surface an additional colour marking mechanism would be necessary in order to implement temporary colour marks on the blade surface. The said colour marks would enable the automatic connection process of the individual images of the blade surface via custom-made software.

### 6.3 Development Issues

The functionality of the developed software was proven during tests at the test facilities of Fraunhofer WKI, however the developing time was long mostly due to difficulties related to insufficient image contrast and image size handling. Due to the subsequent time restrictions, the implementation of the blade marking devices were not integrated on the robot structure and the control system. However this task is regarded a minor development issue which would not cause significant difficulties for future implementation.

**7.0 Publicity**

The Gecko Robot (Ver. 3.5) was presented at the Exhibition LIGNA 2007. The robot was part of the booth of Fraunhofer WKI and formed a very eye-catching and impressive exhibit. The reactions of the visitors were very positive proving the fact that the whole concept has significant commercial success potential.

The following images present the general arrangement of the Fraunhofer WKI booth at Ligna 2007 and especially the Gecko Robot presentation.