# THE POTENTIAL OF SMART CLIMBING ROBOT COMBINED WITH A WEATHERPROOF CABIN FOR ROTOR BLADE MAINTENANCE

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**Keywords:** SMART, robot, maintenance, climb, rotor blade, wind turbine

**Abstract**
The amount of installed wind turbines increases the need for cost effective maintenance [1]. The reliability of mechanical parts, e.g. main bearing, generator, gears and main shaft evolved during the recent years, while the rotor blade maintenance needs to be improved [2]. Since September 2014 a consortium of industrial partners and the University of Applied Sciences Aachen have been developing SMART (Scanning, Monitoring, Analyzing, Repair and Transportation): a maintenance platform for wind turbines. The main goal is the design of a fully functional prototype for a 2.5 MW wind turbine, including a weatherproof cabin. A weatherproof cabin for rotor blade maintenance will extend the annual maintenance period from 8 to 12 month and from 3 to 24 hours a day. One challenge for SMART is sealing the cabin top and bottom against the rotor blade surface. Therefore, a relatively complex structure needs to be attached to the SMART base frame carrying the cabin. The weight of this structure will influence the climbing process. The following study is analyzing these influences in a pratical test with a one to three scaled demonstrator based on motion and force tracking.

## 1. Introduction

SMART successfully completed proof-of-concept milestone by demonstrating the climbing process in December 2015. The SMART demonstrator (see figure 1) - a downscaled model (1:3) - is based on tracked drives to perform continues climbing and weighs around 400 kg. The first figure shows several AR-Marker for motion tracking.

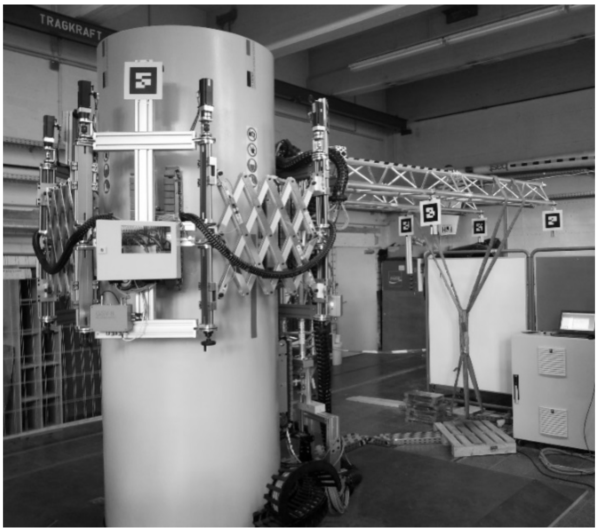

**Figure 1.** SMART Demonstrator (scaled 1:3).

SMART enhances the quality of inspections and repairs. State-of-the-Art technology for inspection, like ultrasonic- and terahertz-spectroscopy, X-ray, and thermography, can be installed inside the sealed cabin in order to support the maintenance procedure. Technology, used during the rotor blade manufacturing process, may be scaled down and integrated into the platform as well, to avoid expensive and time consuming disassembling of rotor blades for a full-inspection. The structure and surface of rotor blades are highly complex. Figure 2 shows a SMART modell, scaled down to one to twenty, with opened cabin top and bottom. The sealing is based on several adjustable disks that can be arranged to fit to the rotorblade. The kinematics of the modell are re-engineered based on the force and motion tracking of the demonstrator (see subchapter 5. Conlusions).

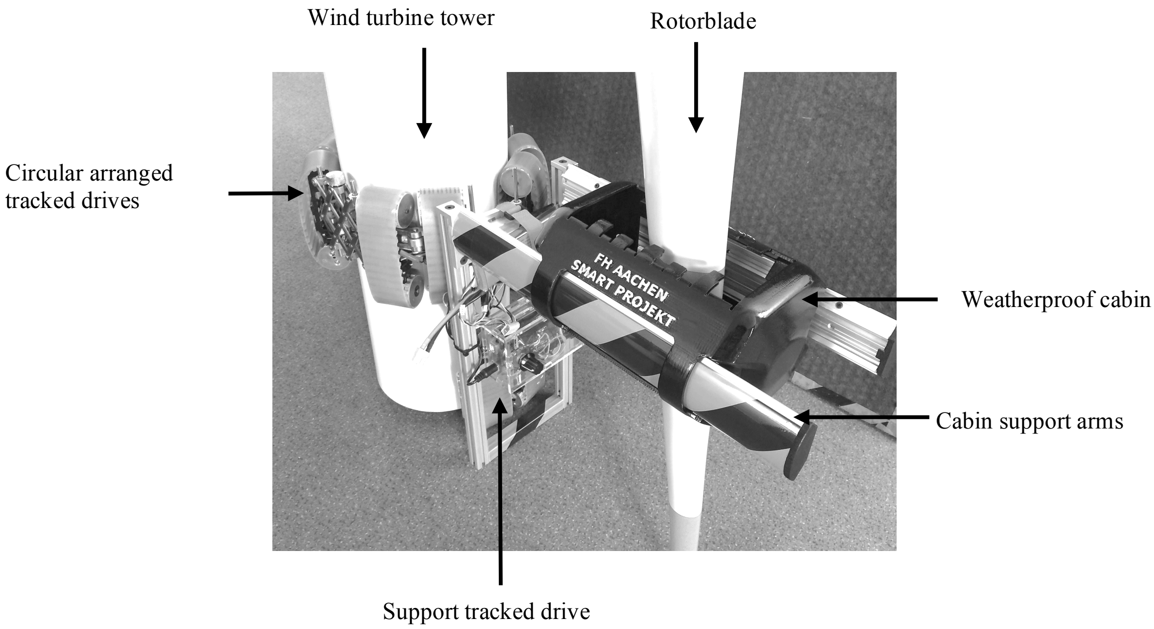


**Figure 2.** SMART Modell (scaled 1:20).

Maintenance processes, like inspection, milling, grinding, bonding and painting require a clean, dry and warm environment. The cabin construction consists of a carbon fiber multi-disk system combined with a flexible sealing lip. This system is sealing the rotor blade at a certain height and is able to move up-and down with the climbing robot. Inside the cabin a human operator can savely perform his work. Further research and development is evaluating the possibilities to employ a cooperative or stand-alone robot system for inspection and repair. Customization of the platform for special applications, e.g. RBE - rotor blade extensions (Energiekontor), full-autonomous inspection and turbine tower maintenance, are part of the challenging development.

The following subchapters focus on the analyses of the climbing process under loaded conditions. The estimated payload for the prototype (1:1) will be around 20 % of the total system weight. This defines the main aim for the following investigation, so a weight of at least 100 kg must be lifted by the one to three scaled demonstrator.

## 2. Motion Analysis of climbing process

The 6D visuell tracking system is based on the ROS (Robot Operating System) tool ar_track_alvar, like described in [3, 4]. Eight markers are attached to the SMART Demonstrator. Four markers are installed at the tracked drives, each attached to one individual drive. They reflect the position of the nearby track drives $A_2$ – $A_5$. In addition four other markers are attached to the extension arm, later referred to as MarkerA – MarkerD (see figure 7). These four markers are mounted in different distances to the main body of the climbing robot. In a later analysis the height of each specific marker is used to determine the bending occurring at the extionsion arm, caused by the weight. The weight is mounted in a distance of 2.5m to the horizontal rotation axes between the extension arm and the main body. The main body is tracked by four high resolution cameras with 2048x2048 pixels at 15 fps. Furthermore a camera with a resolution of 1936 x 1216 and an effective fps of 160 is used to track the extension arm.

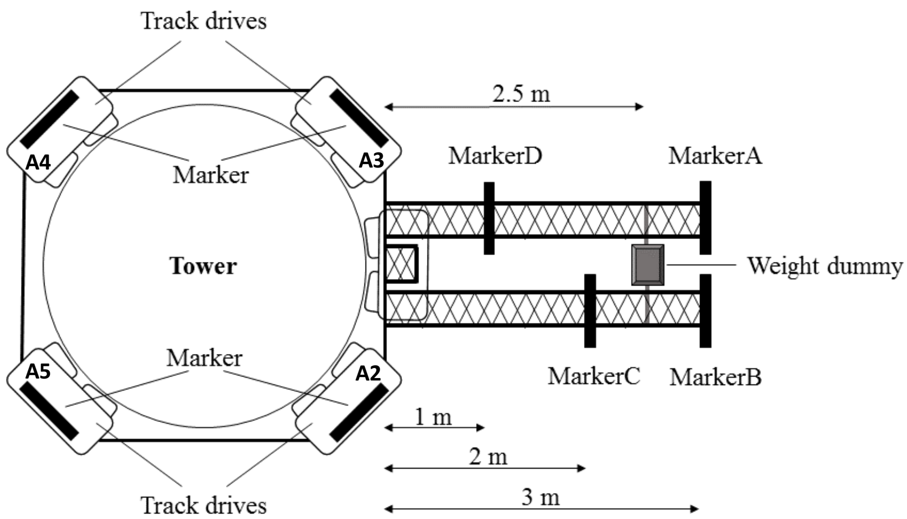


**Figure 3.** Marker and weight dummy attached to extension arm.

### 2.1. Bending from initial load case

Experimental analyses of the motion are essential to validate the results based on calculations and a simulation of the robot system. To determine the influence of the load to the climbing process, a weight dummy of 140 kg is attached to the extension arm (see figure 1 and figure 3). Figure 4 shows the bending of the cabin arms at four positions along the arms. The total weight is added in steps of 20kg. In several test drives the data of the 6D force sensors and the 6D visual tracking data is acquired during the climbing process.

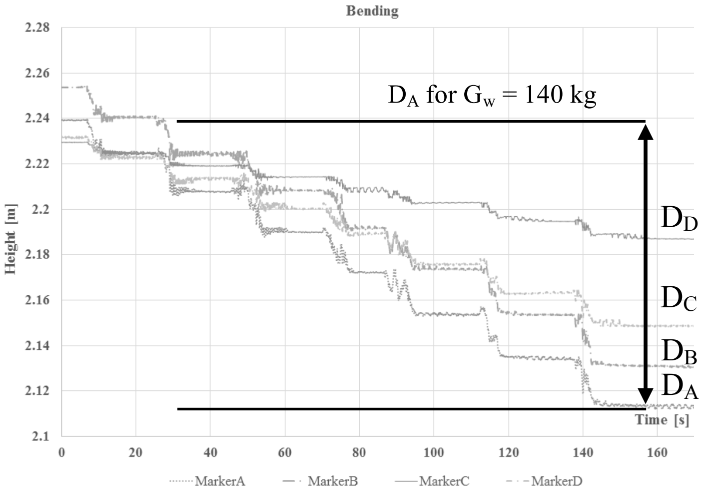


**Figure 4.** Initial bending of the cabin arms.

The idea is to consider the results in the implementation of an advanced controller algorithm to reduce slip and unbalanced forces. In addition the simulated modell is verified by comparing the measurements with the data from the simulation. The verified modell is the basis for scaling the climbing robot up to a 1:1 prototype.

**Table 1.** Measured bending based on figure 4.

| $G_w$ (kg) | Bending (m) | | | |
|---|---|---|---|---|
| | $D_A$ | $D_B$ | $D_C$ | $D_D$ |
| 20 | 0.016 | 0.014 | 0.009 | 0.006 |
| 40 | 0.031 | 0.030 | 0.018 | 0.012 |
| 60 | 0.049 | 0.046 | 0.031 | 0.017 |
| 80 | 0.067 | 0.062 | 0.042 | 0.022 |
| 100 | 0.086 | 0.078 | 0.055 | 0.028 |
| 120 | 0.104 | 0.100 | 0.068 | 0.036 |
| 140 | 0.125 | 0.123 | 0.082 | 0.044 |

The measured bending displayed in table 1 correlate quite well with the estimated results from an FEM analyses using ANSYS (see figure 5).

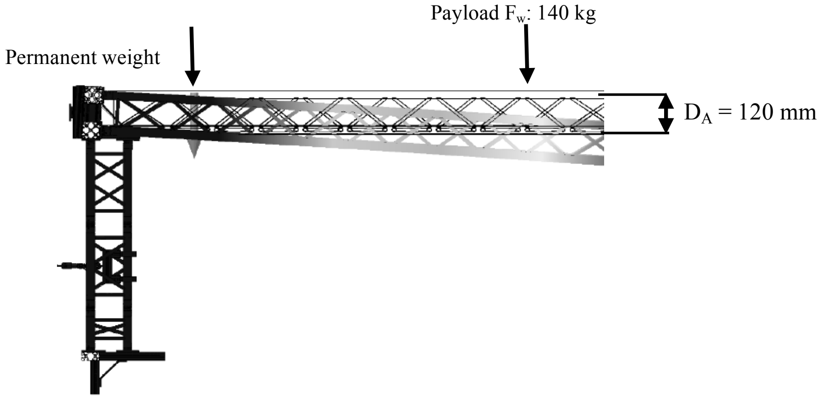


**Figure 5.** FEM Analyses of cabin arms (bending scaled 10:1).

The bending in table 1 is measured at distances $D_A$ – $D_D$ to the main body, which correspond to the mounting points of MarkerA – MarkerD. Therefore a force $F_w$, which represents the weight of the weatherproof cabin is attached to the cantilever arms. The distance between the main body and the application of the force coressponds with the mounting point of the weight dummy.

## 2.2. Measurement results from motion tracking

Figure 6 displays the travelled height of the four track drives for two test drives. The left figure shows a normal lifting procedure with the current demonstrator. On the right the motion behavior is displayed for a 140 kg weight dummy attached to the cantilever arm.

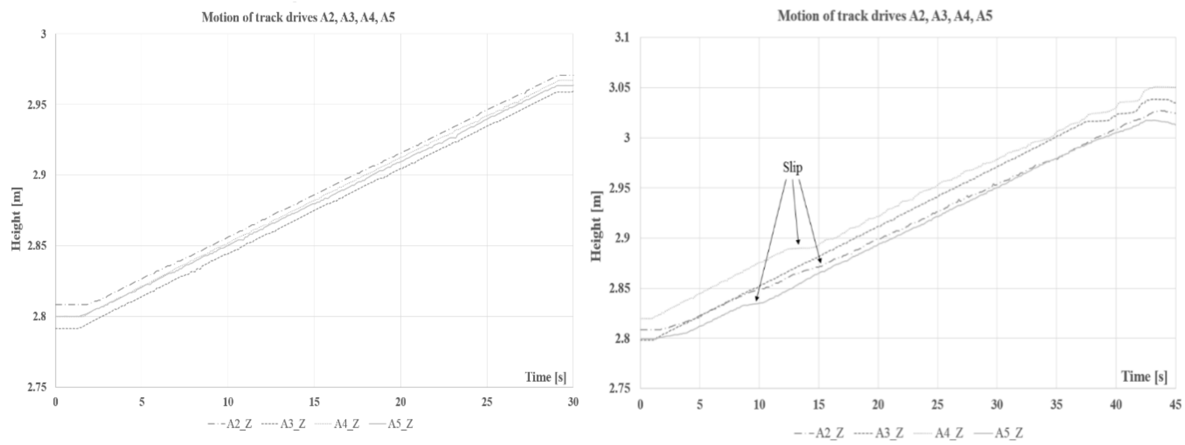


**Figure 6.** Test drive without load (left) and a weight dummy (right).

## 3. Force analyses of climbing process

In each drive, a 6D force sensor, K6D68 10kN/500 Nm from ME-Systems, is used to measure the individual lifting force in relation to the orientation of the drive and the normal force. Hence, the system is based on a friction based climbing process, a higher normal force allows higher lifting forces. The maximum lifting force is limited by the torque of the motors. The customized sensor can measure loads of up to 20 kN forces. In the current design a ball joint is mounted on top of the 6D sensor.

## 3.1. Measurement results from force tracking

The following figures show the results of the normal forces for a climbing process without load (left) and with a weight dummy of 140 kg (right). The normal forces for drives A4 and A5 rise by 2000 N due to the momentum of the weight dummy. Figure 7 displays the normal forces with a negative sign. During the climbing process several non linearities occur due to the slip of the drives, discovered from the data of the motion tracking.

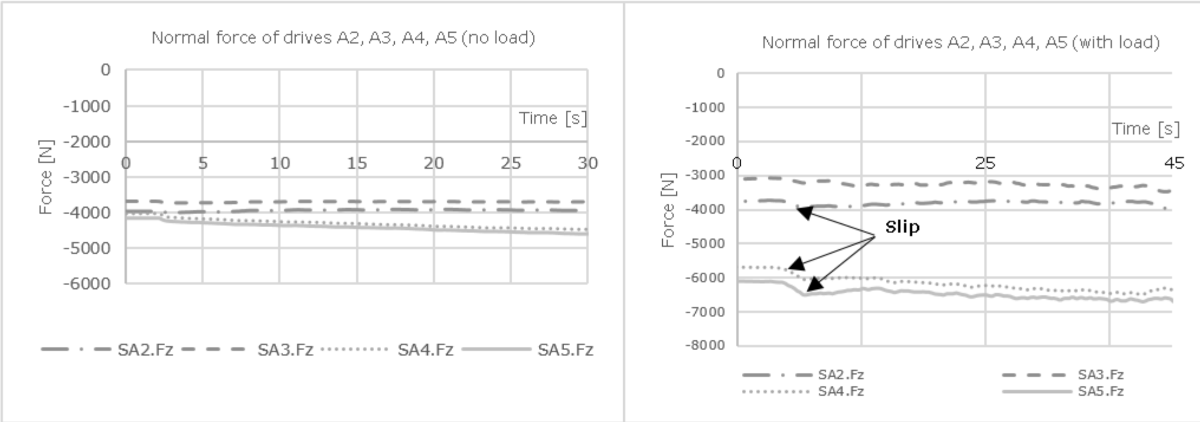


**Figure 7.** Test drive without load (left) and a weight dummy (right)

### 3.2. Cabin load sensor

Figure 8 shows the load sensor of the cabin arms. The system consist of two cantilever arms, which form an extension arm. The used model has a relatively low weight in relation to bending and torsion stiffness. The link between the extension arm and the base body of the climbing robot includes a horizontal rotation axes. The vertical support of the extension arm is connected to the climbing robot by a 1D force sensor.

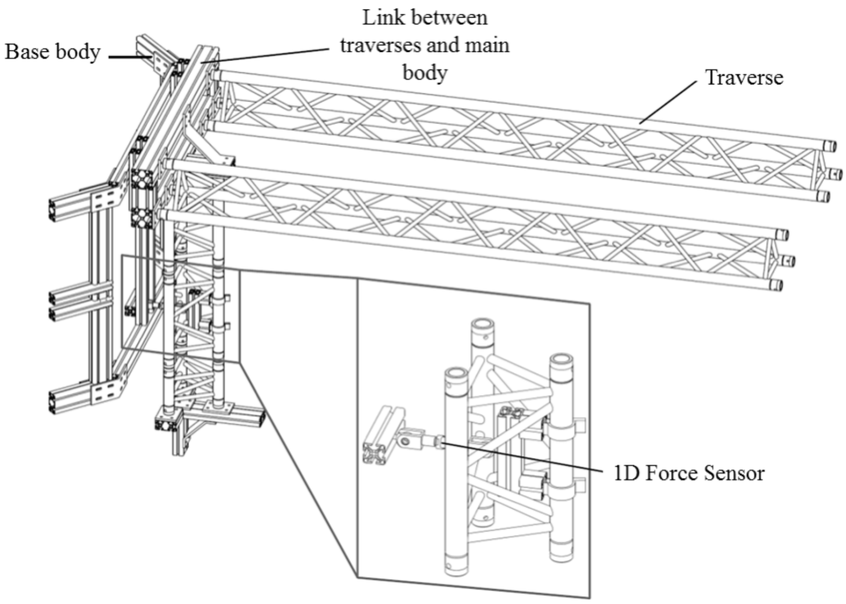


**Figure 8.** Load sensor for cabin.

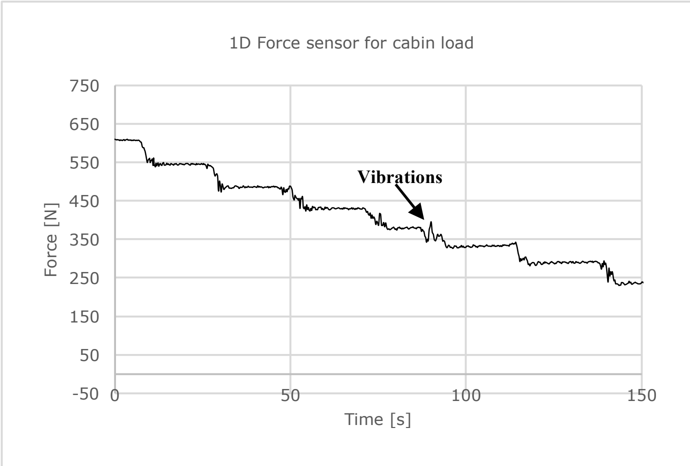


**Figure 9.** Measurments of the initial load with force sensor.

The measured force depends directly from the momentum to the climbing robot. Further research and development will consider the momentum for the control of the climbing process.

## 4. Results

The results show that the SMART demonstrator climbing robot can lift a 140 kg payload. The maximum is not reached, yet. 140 kg payload are 25 % of the 540 kg total system weight. The estimated goals for the system are achieved. This study shows that the mechanism is as efficient as expected. The payload of SMART can be extended up to 350 kg considering the maximum torque of the drives. In addition the tensioning system must be changed to create a higher normal force. The controller must be adjusted to reduce slip. Comparing the results from motion and force tracking during the climbing process shows that slip between the surface of the wind turbine tower and the drives occur. Combined with the slip of the tracked drives the normal forces change rapidly and cause a non-linear pressure distribution on the wind turbine tower.

Despite the pressure distribution on the tower the slip also causes an unbalanced force distribution and vibrations. Vibrations of cabin arms cause even higher momentums on the turbine tower. Therefore, a system must be designed to compensate these vibrations.

## 5. Conclusion

The kinematics of the SMART model presented in figure 2 are more complex than in the previous version of the 1:3 scaled demonstrator (figure 1).

The friction based climbing system can be split into two subsystems. The tensioning system and the climbing system. A tensioning system task is to provide the essential normal force for static friction between the tower surface of the wind turbine and the climbing system. The climbing system can either work intermittent or continuous.

The results show that the movement of certain key-points during the operation of the SMART is hardly predictable. One reason are the missing individual connections of the tracked vehicles to the tensioning system. Instead they are connected via a single ball joint. Instead of having one ball joint for a tracked drive, the required degrees of freedom for a movement are represented on both, the left and the right drive, with individual ball joints. Additionally, a joint rod is used to restrict the motion capability and enable skid-steering for the tracked drives (see figure 10). This development is already done for the SMART model in 1:20 scale.

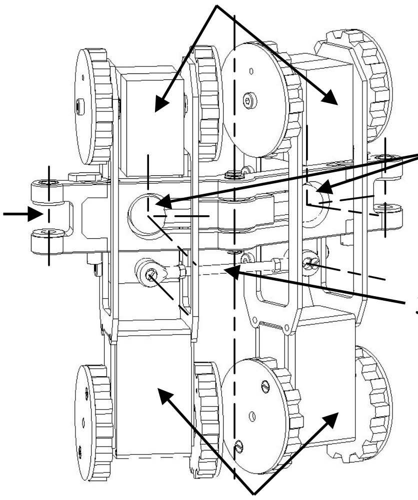


**Figure 10.** Optimization of tracked drive kinematics (scaled 1:20).

The cabin construction must be lightweight and can e.g. consist of a carbon fiber multi-disk system combined with a flexible sealing. This system seals the rotor blade on a certain height and is able to move up- and down with the climbing robot. Further research and development is evaluating the possibilities to employ a cooperative or stand-alone robot system for inspection and repair duties.
The motion and structural analysis show that the climbing process with an attached payload requires an advanced controller strategy for the tracked drives. The cabin weight causes the drives to slip. The system can handle relatively high payloads, but slip must be compensated to balance the SMART climbing system horizontally.

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