Developing a climbing maintenance robot for tower and rotor blade service of wind turbines

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Abstract: Today, more than 275.000 wind turbines generate over 400 GW electrical power worldwide [1]. So the demand for maintenance constantly raises. Since September 2014 the University of Applied Sciences Aachen and industrial partners develop SMART (Scanning, Monitoring, Analyzing, Repair and Transportation), a maintenance platform for wind turbines. The research project is funded by the German federal ministry of economic affairs and energy (BMWi), to support the upcoming industrial needs. While the reliability of the mechanical parts, like main bearing, generator, gears and main shaft increased during the recent years, the maintenance and improvement of rotor blades should be improved. A weatherproof cabin for rotor blade maintenance can extend the annual maintenance period from eight to twelve months, a major goal of the SMART development. In addition, a unique climbing mechanism for conical shaped, thin and slippery surfaces is generated and tested. SMART successfully completed the proof-of-concept milestone by demonstrating the climbing process in December 2015.

Keywords: climbing, robot, rotor blade, wind turbine, maintenance, service, tracking, ADAMS, chain drive, ROS, ar_track_alvar

1 Introduction

The wind market is growing rapidly. In China, the annual growth is about 45 % [1]. The technology of generating electricity from wind power is still young. The amount of installed wind turbines raised the need for maintenance.

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]. The SMART demonstrator is a downscaled model (1:3) for research and development. 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 extends the annual maintenance period from eight to twelve months and from three to 24 hours a day. In addition SMART can increase the quality of monitoring rotor blades: state of the art technologies for inspection, like e.g. ultrasonic- and terahertz-spectroscopy, X-ray and thermography, may be established to support the engineers and technicians. Rotor blade manufacturing procedures can be scaled down and integrated into the platform, in order to avoid expensive and inefficient dismounting of the rotor blades for full-inspection, repair and replacement. Further research and development is focusing the possibilities of a cooperative or stand-alone robot systems for inspection and repair duties. Customization of the platform for special applications, e.g. RBE - rotor blade extensions (Energiekontor), fully autonomous inspection and turbine tower maintenance are part of the challenging development.

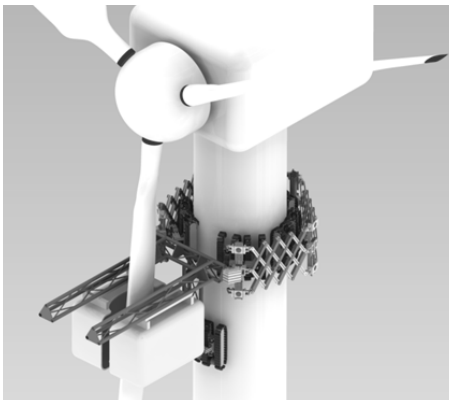


Fig. 1. SMART climbing robot

The following two subchapters intend to summarize general principles for the climbing robot design and associated research and development topics.

1.1 Kinematics of the climbing robot motion

SMART is a novel mobile robot design. One application for this kind of robotic system is the monitoring and maintenance for the rotor blades and the tower of wind turbines. There are two possible solutions to climb a wind turbine – either by using ropes from the top or by climbing based on friction.

The robotic system SMART uses a frictional connection to the tower. Such mechanism can be split into two subsystems: the tensioning system and the climbing system. The intention of a tensioning system 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 be intermittent or continuous.

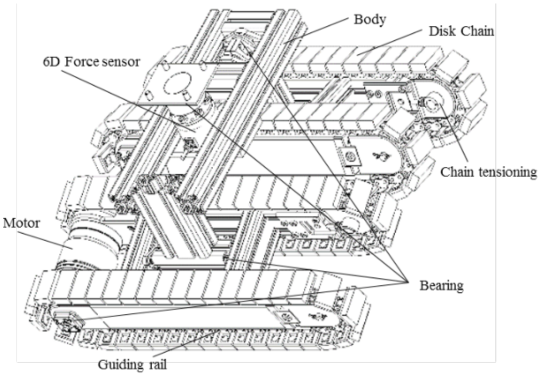


Fig. 2. Dual tracked drive of SMART robot

The following approach introduces a continuously climbing system, based on a tracked vehicle design. Parts of the tracked drives are: chain disk, harmonic drive motor, guiding rails, chain tensioning mechanism, body, bearings and a 6D force sensor.
Many wind turbine towers are conically shaped. Therefore a major requirement for the SMART robot is to continuously decrease the perimeter of the tensioning system, while climbing up. In addition, the attachment and suspension of the tracked drive must permit a pitch angle towards the tower axis around 5 to 15 degrees. There are several other scenarios and circumstances that will require further degrees of freedom, e.g. skid-steering to climb horizontally.
In the following a kinematic model of the climbing robot will be explained, simulated and experimentally tested for scientific prove. Figure 3 illustrates the degrees of freedom of the current robot design that belong to the chassis frame of the tracks. Axis one and two are required to compensate different tower perimeters and to allow the tracks to contact the tower tangentially. Axis 3 is required for the relative pitching between two tracks during the steering process. The necessity will be underlined later with the virtual model in ADAMS ATV. Finally, the spherical ball joint (axis 4, 5, 6) is required to let the tracked drives move relative to the tensioning system.

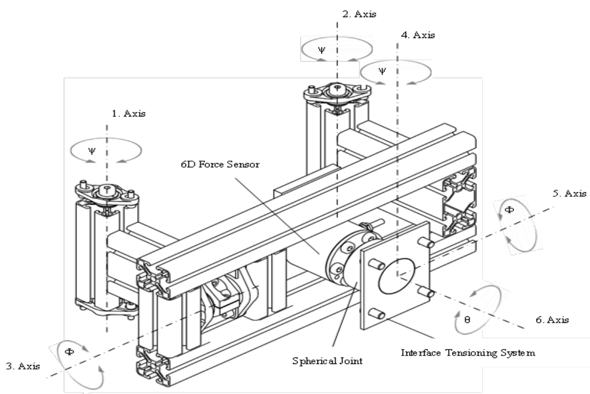


Fig. 3. Kinematic Model of Chain Drive Chassis Frame

The interface to the tensioning system is mounted on top of a 6D force sensor to measure the forces and momentums induced by the robot movement. The kinematic model for the tensioning system, derived from the “Nurnberg Scissors” principal, is displayed in 2D in figure 4.

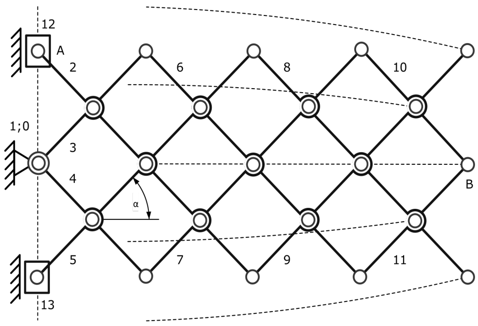


Fig. 4. Kinematic Model of Tensioning System

The climbing robot consists of around 95 moving parts, 49 revolute joints, 6 screw joints, 5 spherical joints, 12 translational joints and 17 fixed joints.

1.2 System Dynamics of SMART Demonstrator

Similar to the experimental SMART demonstrator, shown in figure 12, a model is derived utilizing ADAMS (acronym of Automated Dynamic Analysis of Mechanical Systems).

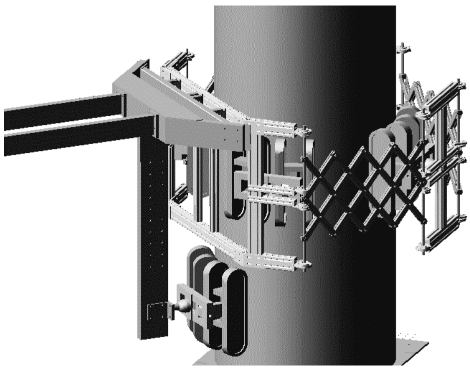


Fig. 5. Virtual SMART Model (ADAMS)

The virtual model possesses the same links, joints, masses and forces like the experimental model. The virtual model will be verified by the experimental demonstrator. The final goal of this process is to establish a valid virtual model to support upscaling into a one-to-one prototype.

2 Modell based Kinematic and Dynamic Simulation

Essential for analyzing the climbing process of SMART are static and dynamic loads (s. figure 6) in combination with a variety of different movements, so called scenarios. A standard scenario for a climbing robot is moving up and down. The movement path is described as a vertical path, parallel to the tower axis. Further scenarios consists of steering or rather horizontally climbing, described by a spiral path around the tower axis. Finally, steering on a conical shaped surface must be analyzed. The static forces shown in figure 6 are expected to change significantly during the steering processes.

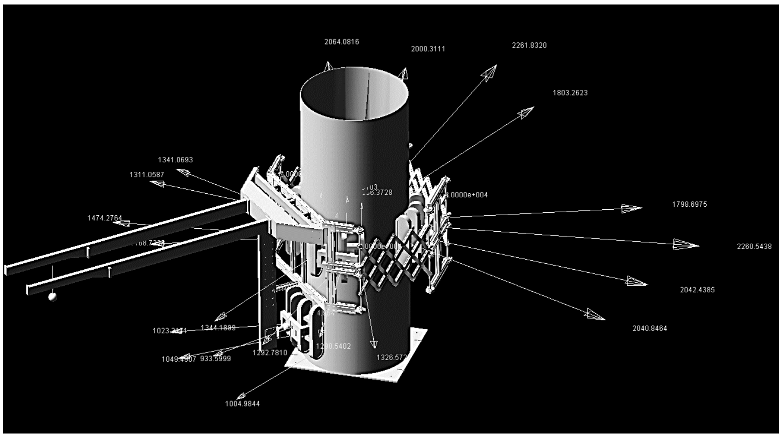
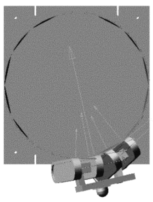
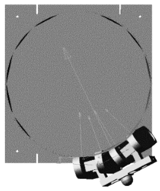
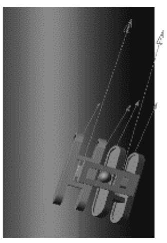
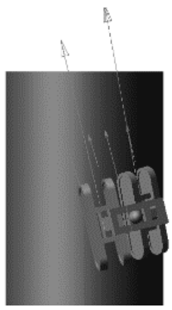


Fig. 6. Static Forces climbing robot SMART

Subsequently to the dynamic simulation many results are shared with ANSYS Workbench, an FEM analysis tool, to optimize the design and the structure of the climbing robot.

ADAMS Tracked Vehicle (ATV) supports the modelling of the climbing robot with a framework to simulate track drives. Table 1 illustrates two similar scenarios, steering towards right and left, regarding normal forces and lifting forces.

Tab. 1. Steering towards Left and Right, "Horizontally Climbing"

	Steering "right"	Steering "left"
Normal Force		
Lifting Force		

The ADAMS simulation shows that the forces are equally distributed between the tracks in both scenarios. The model offers the possibility to track all motions and forces of SMART virtually. To validate these results several sensors are integrated in the experimental demonstrator.

3 Experimental Analyses of SMART Demonstrator

A major goal of the experimental analyses is to validate the simulation and theoretical calculations of the climbing robot. The measurements are split into two parts: Motion tracking and force acquisition.

3.1 Setting up a 3D Vision System for Motion Tracking

The motion tracking is done by a 3D Vision System. It is based on four high resolution cameras, which are used to detect specific landmarks attached to the SMART robot. The task of the tracking system is to identify the 6D pose of each individual landmark in relation to a fixed frame in space – the *world* frame. As a result the motion tracking system provides a punctual observation of the motion process of the SMART robot.

A Manta G609B camera offers Mono8 images with a resolution of 2752x2206 pixels at a maximum of 15 fps [3]. The cameras are mounted around the SMART robot, with individual distances to the robot greater than 3 meters. Camera lenses with a focal length of 25 mm are used. As a result the ROI is covering the whole motion area of the robot. The identification of different landmarks is possible by a binary coding of the markers. Multiple landmarks are mounted at fixed positions of the SMART robot.

Fig. 7. Landmark for Vision Tracking [3]

The software ar_track_alvar [3] of the Robot Operating System ROS [3] includes an open source AR tag tracking library. It is used to determine the 6D poses of the landmarks in relation to the world frame of the camera. The software camera_calibration [3] is used to provide the parameters of the camera system.

The determination of the 6D pose of a landmark with reference to the world frame depends on the 6D pose of the specific camera system in relation to the world frame. The software tf [3] of the Robot Operating System is used to calculate these transformations. In addition, a gyroscope is added to each track drive to validate the tilt angles while steering.

3.2 Force Sensors

The SMART demonstrator consists of five similar drives distributed over the tower surface (see figure 8). The z-axis of the coordinate frame is parallel to the tower axis and is pointing upwards. The Y-axis points in radial direction of the tower towards drive A1. In each drive, A1 to A5, a 6D force sensor, K6D68 10kN/500Nm from ME-Systems, is implemented to measure Fx, Fy, Fz, Rx, Ry and Rz. This customized sensor can measure loads of up to 20kN in z direction. In the current design a ball joint is mounted on top of the 6D sensor. Therefore, the momentums are currently not significant. In addition to the 6D force sensors ten strain gauges are installed in the tensioning system to measure the stress during the climbing process. The feedback from the Harmonic Drive motors delivers absolute position, momentums, acceleration and velocity. In fact, the multiturn absolut encoder feedback is not relevant at this point, because there is still slip between the drives and the tower surface.

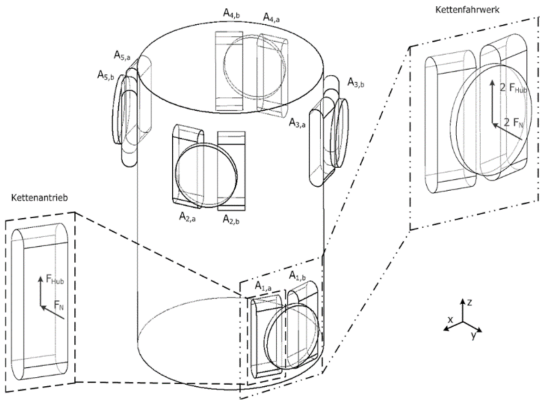


Fig. 8. System overview

The following test results display the current state of development. An advanced controller – based on ROS [3] [4]– is currently established to reduce slip and unbalanced forces for the track drives.

4 Results

The data is generated during a standard climbing scenario test run. The SMART demonstrator climbs 0.6m up and down in around 52s. All drives are controlled manually and started at the same time. The real-time controller is disabled to show the effects of non-linear force distribution. The velocity profile characteristics are: 5% from 7.5s to 22.5s, 15% from 22.5s to 42.5s, 5% from 42.5s to 55.0s (see fig. 10).

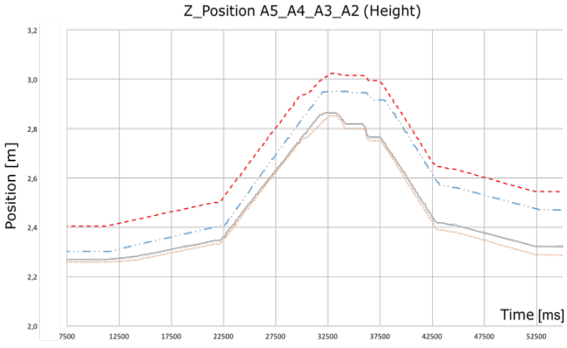


Fig. 9. Motion Tracking of SMART demonstrator

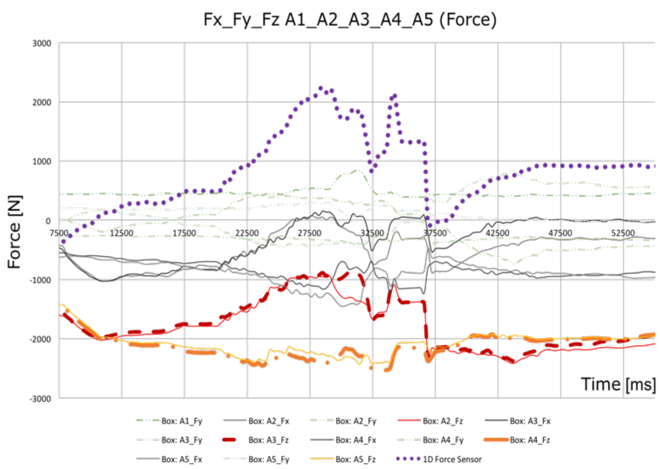


Fig. 10. Force measurements of SMART demonstrator

Figure 10 displays the forces Fx, Fy and Fz for all drives. In addition, a 1D force sensor is measuring the force between the tensioning system and the vertical connection to drive A1 (FzA_1). This force reflects the share of the lifting-force that is generated by drive A4 and A5 on the other side of the tower. This force should be the same for all drives climbing at the same speed. When all front drives A1, A2 and A3, are generate slip – the 1D forces FzA_n raises. The critical point is reached at 27.5s. The height difference of all drives need to be compensated thus resulting in a different force distribution.

The read-out from the SG shows that the tensioning force is rising during the climb and is decreasing during the descent process (fig. 11). In addition, the measurement of the stress in the tensioning system shows the same peaks like the other sensors due to the sudden slip of the drives. This effect is associated with the slight drift of the normal forces in opposite directions. The normal force of A3 and A2 are reduced. At this point the controller of the tensioning system needs to be programmed to raise the tensioning force. In addition, it is necessary to adjust all drives to the same height. Currently, there is no sensor feedback monitoring the height differences of the single track drives. This is only monitored by the global tracking system but will be implanted for a feedback control.

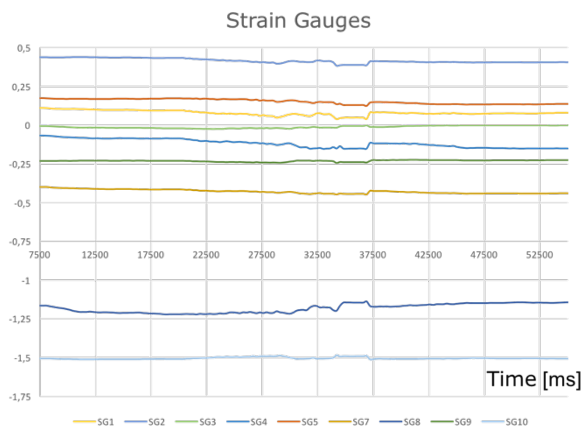


Fig. 11. Strain gauge signals from tensioning system

5 Conclusion and Future Aspects

First test results show, that the SMART demonstrator concept is able to climb vertically based on friction between the tracked vehicle rubber parts and the tower surface (see fig. 12). The results from the tracking system are similar to the movement in ADAMS ATV. Results from the force sensor – without the force feedback controller – differs significantly from the expected values generated by the dynamic simulation.

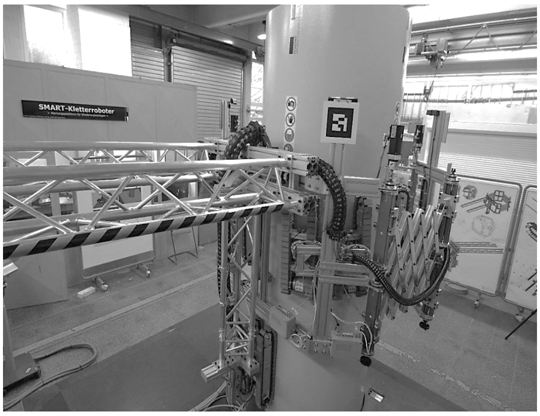


Fig. 12. SMART Demonstrator, scale 1:3

This specific test run shows the necessity for advanced – even model based- control. To generate an equally distributed force over all drives, each motor speed needs to be accurately controlled. The feedback loop actuator consists of the speed control of the motors from the tracked vehicles as well as the motors from the tensioning system.

Pressure sensors are currently implemented on top of the rubber-chain-parts of the tracked vehicle to validate the surface pressure between the tower and the tracked drives.

Subsequently it will be possible to investigate the steering process for further improvement of the SMART kinematics. The validation of the analytical model of the SMART by experimental data will allow the future upscaling of the robot system.

Further steps might include a variety of different maintenance application that SMART can perform, such as: rotor-blade extension, rotor-blade transport along the tower axis, transport of spare parts like e.g. a gearbox or generator and tower maintenance. From this point of view, SMART is becoming more and more a construction robot than just a maintenance platform.

6 Bibliography

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