

3D Realtime Simulation Framework for a Wall-Climbing Robot using Negative-Pressure Adhesion

Daniel Schmidt, Jens Wettach and Karsten Berns

Robotics Research Lab, University of Kaiserslautern, Gottlieb-Daimler-Str. 48, Kaiserslautern, Germany
{dschmidt, wettach, berns}@cs.uni-kl.de

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Abstract: Simulation frameworks are wide-spread in the range of robotics to test algorithms and analyze system behavior beforehand – which tremendously reduces effort and time needed for conducting experiments on the real machines. This paper addresses a component based framework for simulating a wall-climbing robot that uses negative pressure adhesion in combination with an omnidirectional drive system. Key aspect is the adhesion system which interacts with the environmental features such as surface characteristics (e. g. roughness) or defects. An elaborate thermodynamic model provides the basis for a realistic simulation of the airflow between the virtual environment and the vacuum chambers of the robot. These features facilitate the validation of closed-loop controllers and control algorithms offline and in realtime.

1 INTRODUCTION

In robotics, simulation frameworks are important tools to evaluate algorithms e. g. for path-planing or obstacle avoidance without executing them on the real machine. This avoids unnecessary stress on the hardware, reduces testing time and enables developers to analyze system behavior without endangering persons, the environment or the robot itself.

State-of-the-art frameworks facilitate a physically realistic 3D simulation of all kinds of robots, e. g. wheel-driven systems, walking machines, flying and underwater robots, as well as sensor systems and manipulators. But so far, support for the simulation of airflow and resulting negative pressure adhesion in the context of climbing robots is still missing.

This paper presents a framework for simulating CROMSCI¹ – a complex wheel-based climbing robot with an omnidirectional drive, active sliding suction cups and environmental sensors. Its key aspects are seven individual adhesion chambers, inflatable sealings for leak-tightness, built-in suction engines evacuating a large vacuum reservoir and three unsprung steerable driven wheels (Schmidt et al., 2011). In addition to experiments performed with a real prototype, especially the simulation of the interaction between adhesion system and surface allows extensive tests of safety strategies and closed-loop controllers.

¹<http://agrosy.cs.uni-kl.de/cromsci/>

The paper is organized as follows: Section 2 gives an overview of existing 3D simulation tools and applications related to the adhesion mechanism of climbing robots. The general concept of the simulation is presented in section 3. Section 4 describes the setup of the virtual environment and robot model using the SIMVIS3D framework. Afterwards, section 5 presents the thermodynamic model, leakage simulation and physical aspects of the drive system. Section 6 shows the interaction of all simulation components in terms of some experiments. The final conclusion follows in section 7.

2 RELATED WORK

Gazebo (Koenig and Howard, 2004) is a simulator for multiple robots in arbitrary 3D environments with an interface for the control framework ROS. It supports realistic noisy data for different kinds of sensors, e. g. sonar, laser scanners, cameras, Kinect, GPS, RFID and inertial systems as well as rigid-body dynamics for object manipulation via the ODE or *Bullet* engine. *SimRobot* (Laue and Röfer, 2008) is a similar tool based on ODE that focuses mainly on the *RoboCup Soccer* scenario via a realistic simulation of camera disturbances and actuator friction. USARSim (Wang et al., 2003) is the simulation tool for the *RoboCup Rescue* scenario. It is based on the *Unreal* game engine and uses *Karma* for physics.

Concerning commercial tools, *Webots* (Michel, 2004) focuses on research robots as Aibo, Pioneer or Kuka youBot. It uses ODE and provides support for a rather complete set of sensors and actuators. *Vortex*² is tailored to heavy industrial equipment as cranes, excavators and military vehicles. It comes along with its own physics and particle simulation for fluids, dust and shapeable soil. Finally V-REP (Freese et al., 2010) is a feature-rich 3D simulator for wheel-driven, walking and flying robots with support for different kinds of manipulators, sensors and dynamic particles for jet engines, either based on ODE or *Bullet*.

All these tools have the restriction of system dynamics to rigid bodies in common. Although sufficient for collision detection and pick-and-place tasks, negative pressure adhesion as in the case of CROMSCI cannot be modeled. Even the support for particle systems is not suited for simulating the airflow in the vacuum chambers since this is a thermodynamic problem and not related to the particle impulses.

Consequently in the context of climbing robots there only exist individual solutions for computing the adhesion forces. (Longo et al., 2005) uses *Simulink* to simulate the drive system of the Alicia³ robot, but only with a simplified model for the wheel-wall contact and none for the suction cups. (Pretto et al., 2008) calculates the contact forces between the feet of a six-legged climbing robot and a set of adhesive objects via continuous mechanics theory.

(Wettach et al., 2005) presents the thermodynamic model of a wall-climbing robot with 7 vacuum chambers and one reservoir. To evaluate its power a simple 2D simulation had been developed where leakages are only caused by artificial cracks of a certain depth, bounded by two parallel infinite lines. Hence the leakage areas are calculated geometrically as intersection of crack borders and curved line segments of the different sealing sections. Besides the model had been evaluated on a prototype with only one suction cup.

Compared to that work the paper at hand describes a rather realistic simulation of sealing leakages caused by any kind of surface defect (e.g. holes, steps, grooves) modeled in a virtual 3D environment. Their effects are calculated efficiently via a virtual depth camera. Furthermore the dynamics of the drive system are now simulated via a physics engine that takes the downforce resulting from the vacuum chambers and wheel slippage into account. Finally the whole simulation has been evaluated on a highly sophisticated prototype which had been constructed in the meanwhile as 1:1 implementation of the proposed seven chamber model (see figure 10).

²<http://www.vxsim.com/en/software>

3 CONCEPT

The software of CROMSCI has been implemented within the MCA framework³ as depicted in figure 1. The embedded simulation is divided into four logical blocks illustrated as gray boxes. On the highest level ideal actuators are simulated for the drive system, the tool center point (TCP), suction engines and negative pressure valves. User commands are executed by the actuators with a certain delay and within individual velocity limits. The state of the drive units (orientation and velocity of each wheel) can *optionally* be used as input for a physics engine like *Nvidia PhysX* to determine wheel slippage, collisions and the resulting robot pose based on collision and friction models. Otherwise the robot odometry has to be computed manually as input for subsequent simulation steps.

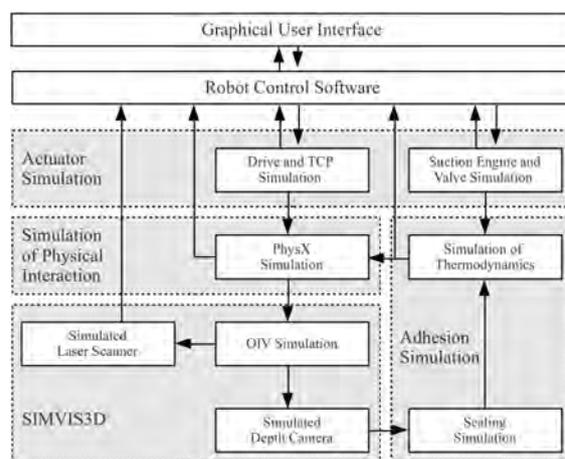


Figure 1: Components of the simulation framework (gray).

Afterwards, the calculated robot pose is given to the SIMVIS3D framework containing the visual scene representation. Via this framework it is possible to both simulate environmental sensors like laser scanners or to visualize the scene. In the context of adhesion simulation SIMVIS3D is used to create a depth image of the surface below the robot, which is the basis for calculating sealing leakages. The simulated leakage values as well as the state of suction engines and chamber valves are given to a thermodynamic simulation. Based on the simulated airflows and negative pressure values an overall adhesion force can be determined which acts as robot downforce in the physical simulation. The modular structure of the simulation framework allows it to replace single components by real hardware to test e.g. the real chamber valves via simulated pressure values. The following sections introduce these components more detailed.

³<http://rrlib.cs.uni-kl.de/mca-kl/>

4 SIMULATION FRAMEWORK

SIMVIS3D⁴ is a framework for simulating and visualizing the interaction of objects in a 3D scene based on the *OpenInventor* standard (OIV) using COIN3D⁵. Its core data structure is a scene graph for arranging elements in the simulated environment and for managing scene changes at runtime. Scene elements are all kinds of OIV nodes: Visual 3D bodies as well as modifiers (i. e. transform nodes) that influence the relative pose of the bodies.

4.1 Scene Descriptions

SIMVIS3D consists of an easy-to-use XML scene description for setting up the scene at simulation startup and of a sound API for applying changes online. These changes are classified as *structural* if elements are added to or removed from the scene and as *parametric* if attributes of existing scene elements are changed, e. g. the six values of the transform node that defines the 3D pose of a robot. All elements that are specified in the XML file or added at runtime are addressed by a unique name through the SIMVIS3D API. Each non-modifier node contains a hook (denoted as *insertion point*) to define the connection of scene elements. This hook is used to locate the correct position in the scene graph. Besides, it serves to make element names unique in the scene so that they can be accessed by the user.

The following excerpt of CROMSCI's XML description illustrates these scene elements:

```
<part file="outdoor_scene.iv" name="WORLD"
  attached_to="ROOT" offset="0 0 0 0 0 0"/>
<part file="cromsci.iv" name="CROMSCI"
  attached_to="WORLD" offset="-1 8 7 0 -90 0"/>
<part file="drive_unit.iv" name="DRIVE_FRONT"
  attached_to="CROMSCI" offset=".3 0 0 0 0 0"/>
<part file="manipulator.iv" name="TCP"
  attached_to="CROMSCI" offset="0 0 0 0 0 0"/>
<part file="empty_node.iv" name="DEPTH_CAMERA"
  attached_to="CROMSCI" offset="0 0 .1 0 0 0"/>
```

Visual elements are specified by the `part` token. The `file` attribute indicates the source of the OIV subtree that represents the new element. It is mounted into the scene graph as child of the *insertion point* node given by the `attached_to` parameter, taking the given static pose `offset` into account. The `ROOT` node is the default top node of the scene graph. Finally the `name` parameter identifies the added part. The use of capital letters is just a convention to highlight parts since they are mainly used as hooks.

⁴<http://rrlib.cs.uni-kl.de/software/simvis3d/>

⁵<https://bitbucket.org/Coin3D/coin>

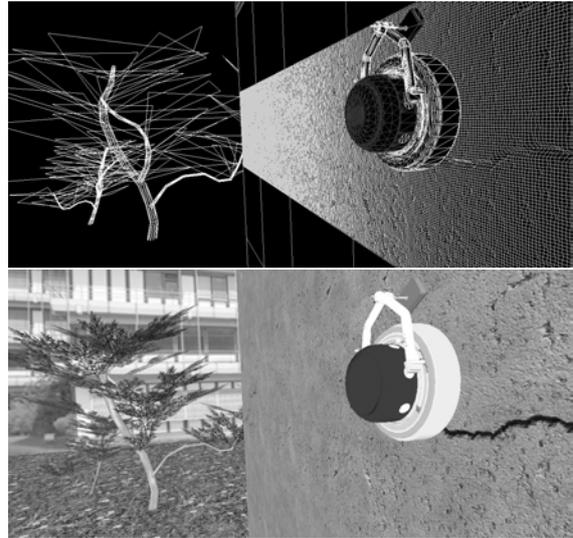


Figure 2: Wireframe model of CROMSCI and a bridge including a band of rough structured surfaces (top) and rendered visualization (bottom).

In the example first an outdoor scene (floor, plants, bridge, pylon) is added to the root as `WORLD`, then the robot is added to the scene as `CROMSCI`. Its drive mechanism consists of three units, each with a driven wheel. They are equally distributed on a circle (see figure 6). Here, only the front drive unit is shown. Actually, the same OIV file is added twice more as left and right unit with corresponding names. For example, the front drive is identified distinctly as `ROOT:WORLD:CROMSCI:DRIVE_FRONT`. Afterwards the manipulator is put into action as `TCP` and then an empty node is applied as anchor for a depth camera. The latter does not represent a visible node since it just serves as virtual hook for the respective sensor. In figure 2 the wireframe model and rendered view of the scene are shown exemplarily.

Whereas the visual objects represent the static part of a scene, modifier elements define the relative pose of subgraphs. Thus they set up the animation of a scene. The modifiable attributes of the elements, i. e. numeric values of transform nodes, are collected in a data array. A link to the values of a specific element can be retrieved via its unique name through the SIMVIS3D API. Therefore, scene changes may be applied from any point in the user code.

In case of CROMSCI the following elements are defined in the XML file:

```
<element name="cromsci_pose" type="3d Pose"
  angle_type="rad" attached_to="CROMSCI"/>
<element name="drive_fr_pose" type="3d Pose"
  angle_type="rad" attached_to="DRIVE_FRONT"/>
<element name="tcp_pose" type="3d Pose"
  angle_type="rad" attached_to="TCP"/>
```

```
<element name="switch" type="Switch"
  switch_mode="-3" attached_to="CROMSCI"/>
```

Each element is attached to one of the parts introduced above. The 3d Pose elements define the (x,y,z) position and $(roll, pitch, yaw)$ orientation (angle values in radians) of their hook. The switch element is used to temporarily deactivate parts of the scene during rendering (according to the original OIV SoSwitch node '-3' means 'on' and '-1' means 'off').

With this setup the climbing robot, its wheels and manipulator can be moved arbitrarily in the scene and the result can be visualized online via a plugin in the MCA user interface. The natural kinematic constraints have to be calculated outside SIMVIS3D. In case of CROMSCI this is done in the Drive and TCP Simulation block shown in figure 1.

4.2 Sensor Data

Apart from the animated 3D scene simulation and visualization the main benefit of SIMVIS3D is the generation of close-to-reality sensor data. So far, cameras and distance sensors (ultrasound, laser scanners, depth cameras) are supported. In the case of CROMSCI the following sensors are relevant:

```
<distance_sensor name="laser_scanner"
  max_distance="4" scan_angle_range="240"
  angular_resolution="0.352423"
  offset="0 0 0.35 0 20 0" attached_to="TCP"/>
<camera name="depth_cam" type="orthographic"
  near_limit="0.1" attached_to="DEPTH_CAMERA"/>
```

The first one is a simulated 2D laser scanner with angular range of 240° and resolution of 0.35° , corresponding to the real Hokuyo URG-04LX scanner. It is attached to the TCP with the given static offset. Hence, the scanner moves over the ground as soon as the robot and/or the manipulator is actuated. The second sensor is an orthographic depth camera attached to the virtual hook. Its data is not exported as from a real sensor, but used internally to calculate the leakage situation of the vacuum chamber sealings arising from the roughness of the ground (see section 5).

4.3 Climbing Robot Scene

The virtual environment of CROMSCI contains different components for simulation and decoration. Figure 3 shows the basic wireframe model of the robot and its surroundings (trees, bridge elements, ground). The bridge pylon consists of single cubes, each with an edge length of 2 m and one structured face. Its defects are modeled as indentations of the rigid body and visualized via textures. This enables to exchange single parts of the bridge for different test conditions.

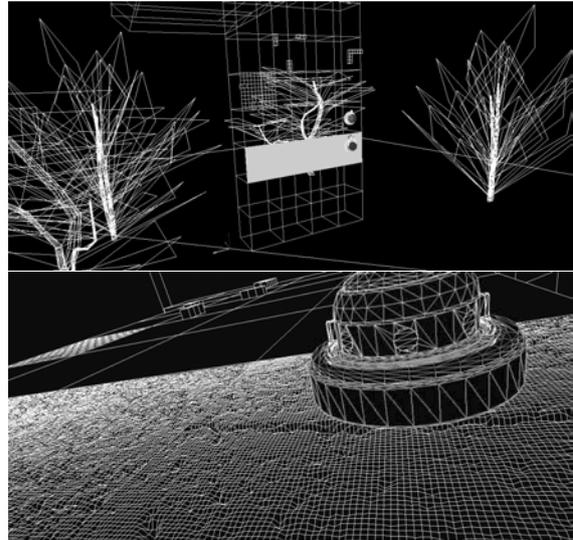


Figure 3: Wireframe model of the environment including the cube elements of the bridge (top) and detailed view of CROMSCI on a rough structure mesh (bottom).

Once created, one can insert a cube at any position and rotate it via the XML scene description as follows:

```
<part file="cube_crack_01.iv" name="CUBE"
  attached_to="BRIDGE" offset="2 0 0 0 0 0"/>
<part file="cube_crack_02.iv" name="CUBE"
  attached_to="BRIDGE" offset="4 0 0 0 0 270"/>
<part file="cube_concrete_01.iv" name="CUBE"
  attached_to="BRIDGE" offset="6 0 0 0 0 0"/>
```

Again, each CUBE is attached to the BRIDGE hook with a certain pose offset. Since these parts do not have to be addressed within the simulation for manipulation, they do not need unique names. For visualization, some additional components are added to the scene in order to create a nice view on the virtual environment. Previous figure 2 shows the wireframe model of CROMSCI and the bridge surface as well as the rendered view including trees, textured surfaces and backgrounds. This visualization is rendered in realtime and is used to observe the simulated scene.

So far, more than 50 different cubes have been created using the modeling tool *Blender* and integrated into the scene description as *OpenInventor* files. Examples are given in figure 4.

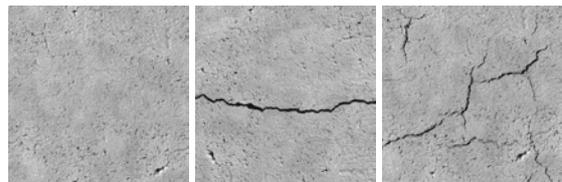


Figure 4: Surface patches with a general roughness, a straight crack and a complex crack structure (from left).

5 INTERACTION OF ROBOT AND ENVIRONMENT

The simulation of robot interaction has to consider different aspects. The most interesting components are those which are responsible for robot adhesion, namely the internal airflow and the occurring leakages. Figure 5 gives a structural view on the adhesion components of CROMSCI. The top view shows the seven negative pressure chambers with one central chamber. Below, the side view illustrates the different mass flows via valves \dot{m}_{V_i} and leakages $\dot{m}_{L_{ij}}$ at the sealing areas. \dot{m}_A denotes the amount of air which is taken out of the vacuum reservoir by the suction engines (Wettach et al., 2005). In general, basic leakages occur even on a perfect flat structure due to the type of sliding coating of the sealing. This leakage increases with surface roughness, defects and gaps.

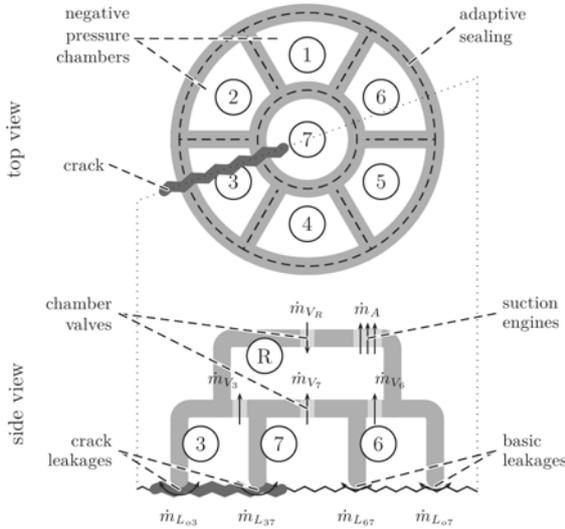


Figure 5: Structural setup of CROMSCI's adhesion components: Adhesion chambers 1 to 7 and reservoir R with an exemplary crack below chambers 3 and 7.

5.1 Airflow and Adhesion Forces

Basis of the interaction model between robot and environment is the first fundamental theorem of thermodynamics and Bernoulli's equation describing the steady state flow of an ideal fluid. The mass flow \dot{m}_{ij} between two volumes i and j depends, according to equation 1, on the current pressure values p_i and p_j and the area of airflow A_{ij} between both volumes. This can e. g. be the sealing leakage connecting one chamber to the ambient air, or the valve opening area between chamber and negative pressure reservoir. Here, ρ_{air} is the density of air.

$$\dot{m}_{ij} = \text{sgn}(p_i - p_j) \cdot A_{ij} \cdot \sqrt{2 \cdot \rho_{air} \cdot |p_i - p_j|} \quad (1)$$

It is now possible to determine the pressure change \dot{p}_i of volume i based on the airflow \dot{m}_{ij} according to equation 2. In here, $\kappa_{air} = 1.402$ denotes the adiabatic index of air, R_{air} is the specific gas constant, T_{air} the temperature and V_i the volume of i . The sum goes over all other volumes k including the ambient air. In case of no direct connection between both volumes k and i (if they are no neighbors) the area A_{ik} and, therefore, also the mass flow \dot{m}_{ik} is zero.

$$\dot{p}_i = \frac{\kappa_{air} \cdot R_{air} \cdot T_{air}}{V_i} \sum_k \dot{m}_{ik} \quad (2)$$

To simplify the thermodynamic model, some of these parameters are assumed to be constant for simulation purposes: Density $\rho_{air} = 1.1883 \text{ kg/m}^3$, gas constant $R_{air} = 287.058 \text{ J/(kg K)}$ and temperature $T_{air} = 293.15^\circ \text{ K}$. More details about the modeling itself can be found in (Wettach et al., 2005). Based on the given pressure values p_i of each chamber it is possible to calculate the total affecting downforce F (equation 3) and its point of action \vec{P}_F (equation 4):

$$F = \sum_{i=1}^7 F_i = \sum_{i=1}^7 ((p_o - p_i) \cdot A_i) \quad (3)$$

$$\vec{P}_F = \sum_{i=1}^7 \left(\vec{P}_i \cdot \frac{(p_o - p_i) \cdot A_i}{F} \right) \quad (4)$$

Here, p_o denotes the pressure value of ambient air ($\approx 100000 \text{ Pa}$), A_i is the suction area of chamber i and \vec{P}_i is the chamber center point related to robot coordinates. The general goal of the closed-loop adhesion controller is to guarantee a certain downforce and to balance the force equally among the three wheels so that the point of action lies in the robot center.

5.2 Sealing Leakages

The leakage between sealing and surface depends on two aspects: The structure of the surface and on the sealing adaptability. Since the interaction between adhesion system and surface is not sufficiently known – especially with respect to friction and sliding characteristics as well as for the influence of different surfaces on the sealing leak tightness – a simplified sealing model is used. The idea is to take a picture via a simulated orthographic camera (see section 4) of the ground below the robot and to transform the depth-buffer from rendering into height data. The depth camera has a resolution of 256×256 pixels and

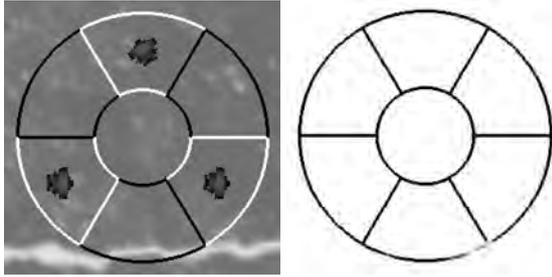


Figure 6: Depth image including sealing area and drive units (left) and resulting leakages (right).

surveys an area of $80 \times 80 \text{ cm}^2$ as depicted in example figure 6, which corresponds to the dimensions of the real robot. Here, one can see the surface height as grayscale image with an overlay of the individual sealing edges (as black and white lines). In the middle of the white marked chambers the three wheels are visible. The other components of the robot chassis have to be removed temporarily by the described switch to take the depth image, otherwise the robot interior would be in sight. The height resolution depends on the near and far limits of the simulated camera. In the present case the observed range is $\pm 5 \text{ cm}$ resulting in a z-resolution of 0.39 mm .

The next step is to simulate the sealing adaption to this height. In reality, the leak tightness depends on the rubber material of the sealing, the induced air pressure and the sliding coating of the sealing. Since these characteristics cannot be emulated completely, an approximation is used which allows the simulated sealing to adapt only a specific portion from one point to another. Depending on a maximum height difference between one pixel and another the height values of each sealing pixel are calculated:

1. set all sealing pixel heights to surface
 - . heights below sealing
2. repeat
3. reset changed flag
4. for each sealing pixel
5. if difference to highest neighbor pixel
 - . larger than maximum height difference
6. set current sealing pixel height to
 - . highest one minus maximum difference
7. set changed flag
8. until not changed

The result of this calculation is shown in figure 6 on the right side. Leak-tight sealing pixels (the distance between ground and sealing is nearly zero) are drawn solid black whereas permeable sealing pixels are colored gray to white depending on the size of the gap. Of course, the total amount of maximal indentation and extrusion of the sealing is limited and has to be considered depending on the real sealing setup. In the present case the maximum capability of the seal-

ing lies at about $\pm 5 \text{ mm}$. Therefore, cracks deeper than this cause a gap which cannot be proofed. Based on these sealing pixels the final leakage L_i of each sealing section S_i can be calculated (equation 5).

$$L_i = l_i \cdot \left(L_{\text{basic}} + \kappa \cdot \sum_{j \in S_i} \frac{h_s(j) - h_g(j)}{|S_i|} \right) \quad (5)$$

Here, l_i is the length of the sealing segment, L_{basic} a basic leakage caused by the sliding coating (the sealing must not be 100% leak-tight otherwise the robot would be stuck), κ is a multiplication factor normally set to 1 which can be adapted for debugging purposes. The sum goes over all pixels j which belong to sealing segment S_i and depends on the height value of the sealing pixel $h_s(j)$ and of the ground pixel $h_g(j)$ divided by the total amount of pixels $|S_i|$ of that segment.

The pressure change p_i of a chamber is then calculated according equation 2 with the leakage areas of the sealing segments of that chamber and the valve area connecting this chamber to the reservoir. In the case of chamber 1 one receives five areas for interchanging air pressure resulting in the sum of airflow given in equation 6 (compare figure 5).

$$\sum_k \dot{m}_{1k} = \dot{m}_{L_{12}} + \dot{m}_{L_{16}} + \dot{m}_{L_{17}} + \dot{m}_{L_{1o}} + \dot{m}_{V_1} \quad (6)$$

Here, \dot{m}_{V_1} denotes the support of negative pressure from the reservoir which is controlled via the valve. On the other side, $\dot{m}_{L_{1o}}$ is the amount of air lost to the outside ambient air. If all chamber pressures are balanced equally, the remaining airflow between the chambers is zero. Otherwise, also these areas produce a certain loss or support of pressure, depending on the individual chamber pressures in left and right neighbor ($\dot{m}_{L_{12}}$ and $\dot{m}_{L_{16}}$) or the center chamber ($\dot{m}_{L_{17}}$).

5.3 Actuators and Robot Behavior

Depending on the real hardware settings all actuators are simulated with certain limitations of acceleration, velocity or position. Therefore, all desired commands for drive steering or valve positioning are executed with a certain delay. Despite this, the actuators are regarded as ideal hardware without tolerances, runtime errors or defects. But it is possible to replace these simulation elements by those producing errors with given failure rates to analyze their effect.

To simulate the system behavior on affecting forces and motions it is possible to apply a physics engine. So far, the climbing robot simulation framework uses *PhysX*⁶ from *Nvidia*, but other engines like

⁶<http://developer.nvidia.com/physx>

*Newton Game Dynamics*⁷ could be used in combination with SIMVIS3D as it has been done in other research projects before (Wettach et al., 2010). In general, the physics engine has to consider and contain the following aspects: Collision models of robot and environment, affecting forces (gravity and adhesion force), friction models and wheel orientation and velocity for locomotion.

Due to simplicity, CROMSCI does not use the same rough structured mesh for physical simulation. The ground surface is assumed to be plane to simplify the wheel-ground interaction. The friction caused by the sealing is also not considered here which affects the robot in real life. Depending on the selected friction values between wheels and surface and on the generated downforce one receives a different robot behavior relative to its motion direction and gravity. For instance, the wheel slip is high while driving up, since the robot has to overcome gravity. In the same way it falls down if the adhesion force is too low.

For debugging purposes it is possible to observe the current state of the physical simulation during runtime via a visualization window showing the complete scene with all actors. One can pause the simulation, walk through the scene and read out current values like pose or velocity of each component. It is also possible to change e. g. the gravity value during runtime or apply an impact to a simulated body.

6 APPLICATION

The presented simulation framework has been created to test control algorithms of CROMSCI offline without the real machine. Figure 7 shows the graphical user interface (GUI) of CROMSCI with a view on the 3D scene and the current robot state. One main application is the validation of closed-loop adhesion controllers. In figure 8 one can see an experimental run in which the simulated robot is driven downwards the rough wall facing a deep crack. The left circular view shows the state of the seven chambers of the adhesion system. The darker the color, the lower the pressure. Numbers 2, 4 and 6 indicate the associated chambers, whereas the dimensions of the black circles in non-labeled chambers 1, 3 and 5 illustrate the downforce at the corresponding wheel. In the first line, this downforce is balanced out by a stronger adhesion at the top chambers (darker color of chambers 3, 4 and 5 compared to 1, 2 and 6) to counteract robot tilt. In the second row, the bottom chambers are located on the crack and lose negative pressure (white chambers).

⁷<http://www.newtondynamics.com>

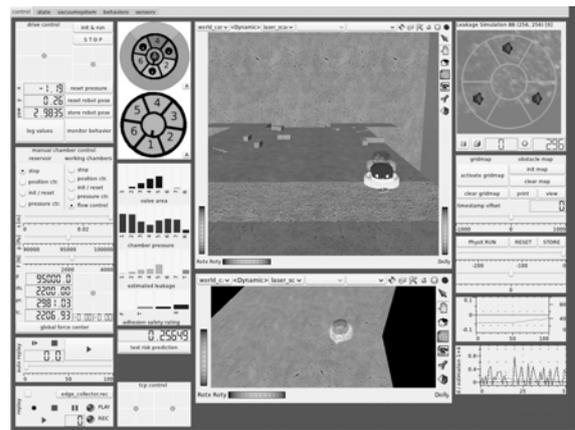


Figure 7: GUI with visualization plugins of the simulated scene (middle), control elements (left), and state information of adhesion (top left) and sealing simulation (top right).

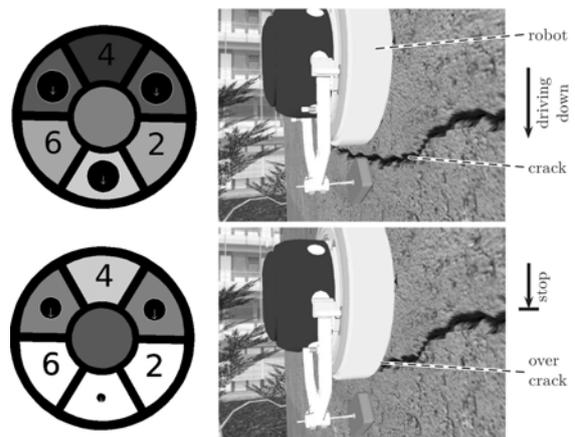


Figure 8: Screenshots of experiment showing the simulated robot CROMSCI driving to a deep crack (right) and current states of the negative pressure chambers (left).

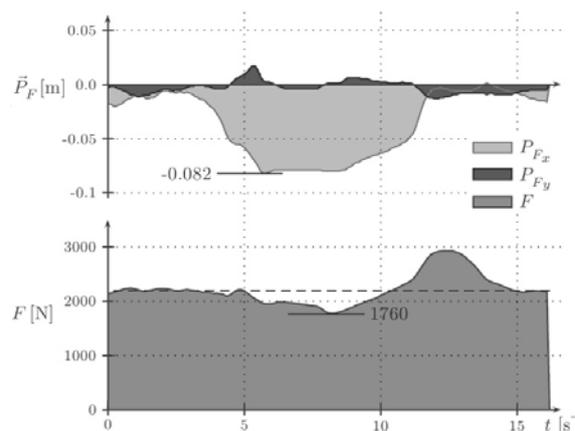


Figure 9: Progress of simulated downforce F and its point of action \vec{P}_F during the presented experiments. Robot tilt leads to a shifted point of downforce in vertical direction from seconds 4 to 12.

Figure 9 illustrates the progress of the downforce value F and its point of action \bar{P}_F . It can be seen that the resulting values are very realistic: The total amount of downforce F is reduced from desired 2 200 N to 1 760 N and the x position of the point of action (P_{F_x}) moves about 8 cm below the robot center.



Figure 10: Real climbing robot CROMSCI navigating on a concrete wall.

In the latest history, the simulation system has e. g. been used to validate safety measures and risk prediction methods (Schmidt, 2013) or to perform a foresighted analysis of the terrain. The accuracy of the thermodynamic model of the vacuum system itself has been proven in earlier experiments (Wettach et al., 2005). The complete simulation framework is accurate enough to optimize the control software in the simulation, so that only some fine-tuning is needed to apply these algorithms on the real machine depicted in figure 10. Some demonstration videos⁸ of CROMSCI in operation prove this transferability of control algorithms from simulation to reality.

7 CONCLUSIONS

This paper presented a novel framework on the basis of SIMVIS3D for simulating a climbing robot using negative pressure adhesion and an omnidirectional drive system. It could be shown that the system is able to simulate the airflows and pressure changes of a complex vacuum system with seven suction cups and one reservoir. The structure of the ground has a direct impact on the leakage values in order to model different surface characteristics. Hence, this tool facilitates the development of control algorithms independent of the real robot and enables an offline and realtime validation in arbitrary 3D environments.

Further work will focus on a porting to FINROC⁹ and an easier handling of the physical simulation,

⁸<http://agrosy.cs.uni-kl.de/en/galerie/cromsci-medien/>

⁹<http://www.finroc.org>

since the *Blender* export of collision objects does not include joints. Additionally, a new robot prototype is under construction: Its control software will be optimized using this tool first, before executing and fine-tuning it on the real system.

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