Semi-autonomous Flying Robot for Physical Interaction with Environment

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***Abstract*— This contribution presents the first results of the development of an unmanned aerial vehicle (UAV) which is capable of applying force to a wall while maintaining flight stability. This is a novel idea since UAVs are used so far only for tasks without physical contact to the surrounding objects. The basis for the work presented is a quadrotor system which is stabilized with an inertial measurement unit. As a new approach an additional actuator was added to generate forces in physical contact while the UAV stays horizontal. A control architecture based on ultrasonic distance sensors and a CMOS-camera is proposed. The performance of the system was proved by several flight tests. Potential applications of the system can be physical tasks at high places like cleaning windows or walls as well as rescue or maintenance tasks.**

Keywords— flying robot, UAV, quadrotor, helicopter, physical interaction, cleaning tasks

I. INTRODUCTION

Tasks which need to be performed at high and difficult to access places generally need significant effort from humans, as they require time and space consuming support systems such as ladders or scaffolding. The risk of injuries to humans by falls is also increased. Therefore working in elevated places is often dangerous and not economically sensible. The development of remote controlled or autonomous systems with the ability to carry out such tasks could solve these problems. Thus no additional support from scaffolding, ladders or platforms would be needed and humans would not be endangered. High versatility would also be an advantage of such a system.

Unmanned Aerial Vehicles (UAVs) are remote controlled, semi-autonomous or fully autonomous flying objects. The size, level of autonomy and the kind of thrust generation can greatly vary between different types of UAVs. These aircraft are most often used for surveillance and reconnaissance, aerial photography, exploring areas, which are dangerous or difficult to access during rescue missions and also for research purposes.

UAVs are a promising type of robot which can be applied to a large variety of tasks. The development of a UAV for physical interaction with surfaces opens up a great spectrum of new application possibilities for this highly flexible technology.

This paper presents such a development. Physical interaction that comprises the application of force to an object such as cleaning, joining, separating or transporting objects, coating (e.g. painting) and inspection of objects and surfaces. The scope of this paper is limited to applying a normal force to a vertical wall, as this is the basic function for mechanical interaction (see Fig. 1).

This contribution is structured as follows: In the next chapter the state of the art of climbing and flying robots is presented. The basic concept of the developed robot is explained in chapter III. This is followed by a description of the hardware platform as well as the suggested control architecture. Experimental results are then presented in the chapter on flight testing.

II. RELATED WORK

Besides rail- or cable guided robots [1], there are different types of autonomous robots suitable for tasks in high places:

A. Climbing Robots

Special robots exist for applications in steel structures, such as bridges, gas or oil tanks. These robots are able to climb by using magnetic forces [2], [3].

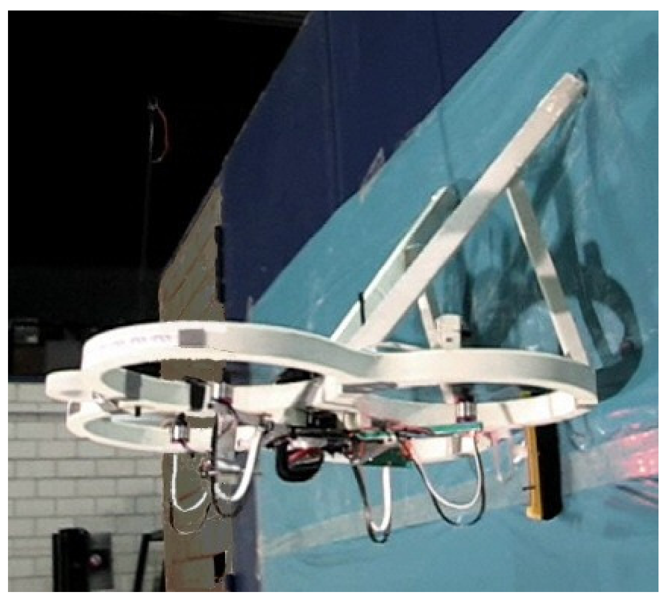

Figure 1. Flying robot applying force to a wall during stable flight

There is also a large number of climbing robots that use an attraction force which is created through vacuum between the robot and the surface [4], [5]. The use of these robots is restricted to smooth surfaces. Two other robots which can be used on rough surfaces are presented in [6], one equipped with a vacuum rotor package and the other using vortex attraction. The climbing robot presented in [7] also uses an aerodynamic principle, the Bernoulli-effect, to create an attraction force.

More novel approaches use electro adhesion [8], which can create adhesion forces on a wide variety of common substrates. Alternatively biologically inspired principles play an increasingly important role: Following the example of a Gecko, peeling kinematics were developed, for example at the Carnegie Mellon University in Pittsburgh [9], and used for creating robots which can climb on irregular terrain.

B. Flying Robots

Autonomous Vertical Take-Off and Landing (VTOL) UAVs are used mainly for reconnaissance and data collection tasks, surveillance and applications in dangerous areas. In order to take off, fly and land autonomously, most of them are equipped with an Inertial Measurement Unit (IMU) and many also with a GPS-receiver and cameras.

The autonomous helicopter *MARVIN* ("Multi-purpose Aerial Robot Vehicle with Intelligent Navigation") was developed at the laboratory for autonomous flying robots at the technical university of Berlin. Application scenarios for this robot are load transport with multiple helicopters, deployment of sensor networks using small scale aerial robots and observation [10].

ARTIS ("Autonomous Rotorcraft Testbed for Intelligent Systems") is a helicopter which was developed at the Institute of Flight Systems at the German Aerospace Center (DLR). The goal of this project is to explore autonomous intelligent functions such as decision making, collision avoidance, collaboration of multiple flying robots and vision-guided navigation [11].

Vision-guided robot helicopters are also being developed at the Robotics Institute of the Carnegie Mellon University to solve tasks like seeking and locating objects while simultaneously avoiding obstacles. Another goal is the manipulation of objects during autonomous flight [12], [13].

The UAV swarm health management project at the MIT investigates automatic cooperative action of several quadrotors together with ground vehicles or ground stations. The cooperatively acting quadrotors are capable of returning to a service station on the ground to recharge their batteries, flying together in different formations and following vehicles on the ground or in the air [14].

C. Flight-type Wall-Climbing Robots

Prof. Nishi of the University of Miyazaki, Japan, developed propeller driven climbing robots which are capable of flying over obstacles in order to reach a wall and then to climb up this wall. The propellers allow for a soft landing, in case the robot loses contact with the wall. The robots are 10 m long, weigh between 16-20 kg and can transport a payload of up to 2 kg. Combustion engines are used to drive the propellers. The planned application scenarios for these robots were short response time rescue and fire fighting operations on high-rise buildings [15].

III. CONCEPT

The climbing robots presented in the previous chapter can execute physical interactions with objects where-ever they are deployed. The application possibilities, however, strongly depend on the type and structure of the surface. Large obstacles may also prevent these systems from fulfilling their function. Furthermore, the target location needs to be reached by climbing, which seriously limits locomotion speeds. Exceptions to this rule are Prof. Nishi's flight-type robots which can overcome obstacles by flying over them. However, due to their length of 10 m they cannot be very flexibly used.

Flying robots (UAVs) like the ones presented above can fly fast to places which are high and difficult to access. They are independent of object surface as well as of obstacles. However, presently these robots are usually not capable of executing physical interaction when they reach their target position.

The goal of this work is to develop a flying robot which is capable of reaching high places on a wall or a glass surface quickly in order to execute a physical task while hovering at its target location. As a first step toward achieving this goal, the UAV is designed to execute a task on a smooth and vertical surface in an indoor environment. Wind influence will be considered in future designs.

To achieve good dynamics and high versatility, the system should not exceed a maximum side length of 750 mm and should be capable of carrying a payload of 200 g (for example a cleaning brush). It must also be possible to precisely remote control the system while applying the necessary contact force to fulfill the task.

A quadrotor of the type "Mikrokopter" [16] was used as a basis for this development. These UAVs normally contain an integrated flight stability control system and offer the advantage that a frame can easily be designed to protect the rotors and to mount the interaction tool (brush). Compared to classical helicopters with a tail rotor that creates a continuous drift, a quadrotor can easily hover in one position.

IV. PHYSICAL PLATFORM

A. Basic Quadrotor Module

A quadrotor has four propellers arranged in a square plane with each rotor pair turning in opposite directions, allowing compensation of torque. Motions are produced by variation of individual rotor speeds. The four propellers have a diameter of 10 in. each and are propelled by four brushless DC motors.

At the center of the system is the FlightControl, a board equipped with a microprocessor and an IMU, which consists of three gyroscopes for the three axes of rotation (pitch, roll and yaw) and a 3-axis-accelerometer. Using the gyroscope values, unwanted rotations of the quadrotor are recognized and compensated. Using the accelerometers, the UAV can automatically take up its horizontal position.

B. System Extensions

In normal flight, movements are executed by tilting the UAV's flight plane. This is problematic when coming into contact with walls or objects because the UAV can be sucked against the wall towards which it is tilted, leading to a crash. The reason is that the propellers of the quadrotor create a low pressure area above it. As a novel approach to solve this problem, we propose a quadrotor equipped with an extra propeller for horizontal thrust (see Fig. 2) which is effective even in close proximity to walls.

The horizontal propeller unit consists of a DC motor and a 5 in. propeller. The propeller was positioned in the rear area so as to be at the height of the brush attached at the front, thereby creating almost no tilting moment during wall contact. The brush is used to exemplify physical interaction.

A glass fiber reinforced foamed polystyrene frame is used to carry the extra modules while also providing protection for the four main propellers. Two supportive foamed polystyrene beams were added to prevent tilting of the UAV during wall contact.

For autonomous flight, ultrasonic range finders as well as a wireless CMOS-camera were added to collect data on the quadrotor's environment. The ultrasonic sensors can measure the height of the flying robot and the distances to walls or obstacles in front and at the left/right side of the UAV. They are accurate up to a range of five meters.

Since the FlightControl is used at its full capacity, a second microcontroller ("µC" in Fig. 3) is necessary to collect and treat the data from the ultrasonic rangers and implement the control loops for yaw and the horizontal propeller. It uses a 433 MHz wireless connection to acquire commands from the user and send sensor data back to the ground station.

In Fig. 2 all the components of the flying robot are showed. The UAV's width is 600 mm, its length 650 mm and its height 600 mm. Its weight totals at 1.4 kg.

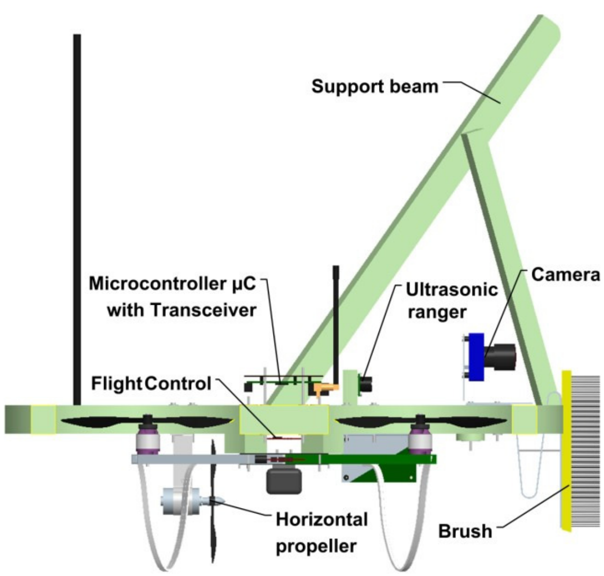

Figure 2. Cross-section of the complete flying robot

V. Proposed Control Architecture

A. Open Loop Control

The system architecture of the flying robot is shown in Fig. 3. The quadrotor is normally piloted by passing the four values nick, roll, yaw and throttle to it via the 35 MHz wireless connection. Theoretically one could implement a control loop to use only the four values for autonomous positioning and physical interaction with surfaces. In part IV (b) it was shown that this is not sensible and therefore an additional rotor has been added to the back part of the UAV. This leads to a fifth command for the horizontal propeller speed.

The basic quadrotor was also equipped with an additional microcontroller "µC" as described in section IV (b). This should allow piloting via the ground station and implementation of the control loops. The ground station is formed by a PC equipped with a USB remote control and a 433 MHz transceiver which on the one hand passes the commands to the UAV and on the other hand receives the sensor data from the UAV. The microcontroller (µC) is connected to the FlightControl (FC) to pass on commands. The horizontal propeller ("M" in Fig. 3) is controlled directly by the microcontroller (µC) using an amplifier. The measurements made by the ultrasonic rangers ("X1", "X2", "Y1", "Y2" and "Z1") are sent back to the ground station by the microcontroller.

B. Closed Loop Control

To support the pilot during maneuvers close to walls, additional control loops are being developed. The basic flight stabilization detailed in chapter IV (a) stays active. The pilot can activate the automatic flight support, handing over the commands for throttle, yaw or the horizontal propeller to the

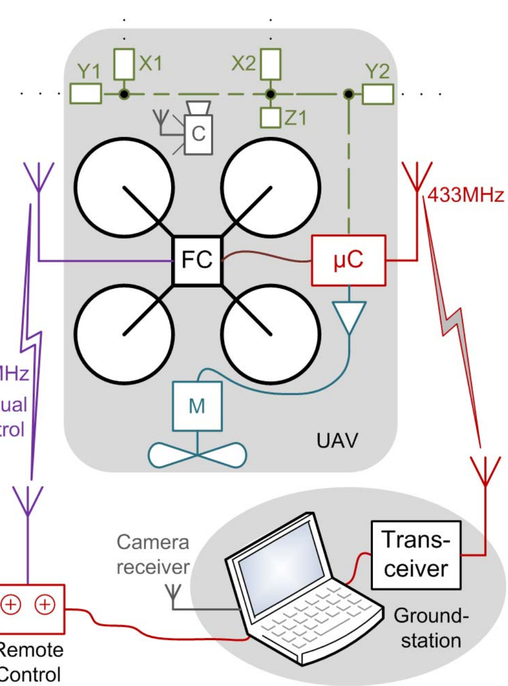

Figure 3. System architecture. FC=FlightControl, µC=microcontroller, M=horizontal propeller, C=camera, X/Y/Z=ultrasonic rangers

ground station and the microcontroller (µC). The pilot then only provides set points for the closed loop control using the remote control. Nick and roll continue to be manually operated, but if the pilot wants the UAV to stay in one position, nick and roll are adapted automatically in order to compensate drift.

The closed loop control of the UAV is divided into four sections (see Fig. 4): The first is the control of the distance to a wall (x-axis position, "Horizontal propeller"), followed by a control of the angle of the UAV to the wall (yaw control), thirdly a height control ("Throttle") and lastly a drift compensation.

The priorities of the individual processes are the following: Transmitting the manual commands receives highest priority since these are absolutely necessary to the system's function. The next highest priority is given to the control loops so as to guarantee low response times when they are active. Output to the user interface and other secondary functions receive the lowest priority.

The first automatic flight support is used for controlling the horizontal propeller. When this support is activated, a PID controller implemented on the microcontroller (µC) generates commands for the horizontal propeller. The setpoint is given by the pilot and the real values are acquired using the ultrasonic range finders. This control loop should allow acceleration of the horizontal propeller within given bounds so as to bring the UAV to its position in x-direction.

The yaw control is the second automatic flight support, which uses a second PID controller to correct the UAV's angle to the wall. The aim of this control loop is to maintain the UAV parallel to the wall so as to be able to precisely reach points on the wall. The output value is a yaw value that is generated using the error angle (α_{set} - α_{actual}). It is passed on to the FlightControl by the microcontroller. The actual angle is calculated using data from ultrasonic rangers in the x-axis attached to the left and right of the UAV.

The third automatic flight support is the throttle control, which uses data acquired either from the image processing or from the ultrasonic ranger in the z-axis. This control loop is implemented on the ground station as the microcontroller's performance is unsuitable for image processing tasks. The calculated throttle values are then passed on to the FlightControl via the microcontroller (µC).

Due to the use of accelerometers and gyroscopes to estimate the UAV's position and orientation, the appearing drift has to be compensated. Therefore a closed-loop control of the distance to surrounding walls using ultrasonic rangers is developed. The choice of an ultrasonic ranger-based drift compensation is justified by the fact that this solution is only necessary indoors as position control for outdoor maneuvers may be implemented using (D)GPS or similar techniques. The so far implemented control loop has also proven very effective as a collision avoidance system during manual flights (see Fig. 5): When the flying robot comes closer than an adaptable threshold to obstacles, the control loop generates an impulse in the other direction with the particular steering value.

C. Processing Data from the Ultrasonic Range Finders

Since the values delivered by the ultrasonic rangers occasionally contain outliers, these must be filtered and adapted to the limits of the measurable area before they can be used as inputs for the control loops. The filter should allow a good correction of errors, have a minimum effect on plausible values, require little computing power and generate a minimal delay.

In order to select an appropriate filter several algorithms were analyzed and compared. The selected filter combines good performances and a low computing power. Fig. 6 shows the measured raw data and the filter output during a typical flight maneuver near a wall.

D. Image processing

The data from the camera is to be used as input for the throttle control. In order to implement this, reference structures such as edges or lines must be detected in the image. To do so the picture is first treated with the Canny algorithm [17] so as to obtain a binarized edge picture. This algorithm consists of four main steps:

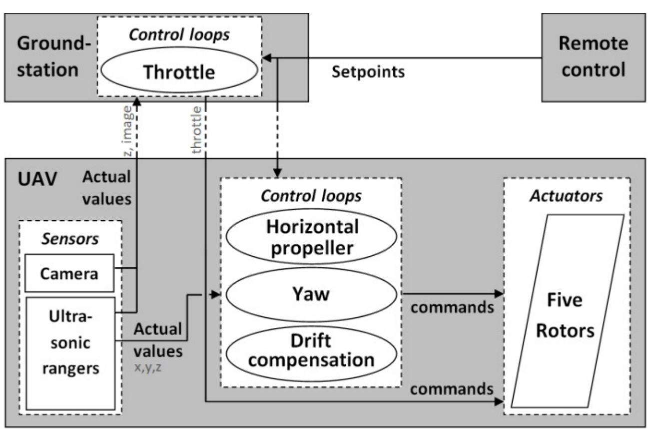

Figure 4. Control architecture

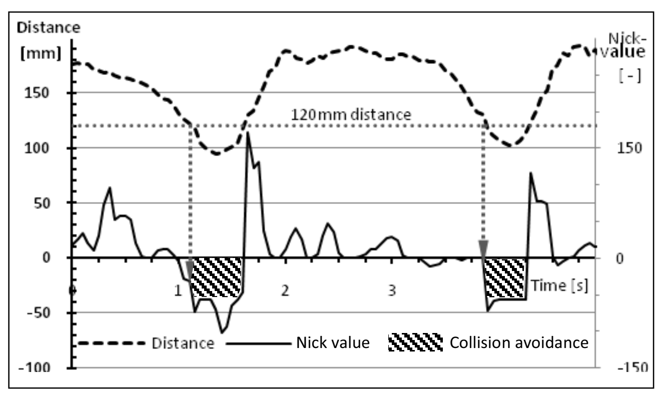

Figure 5. Example of the collision avoidance: coming closer than 120 mm to obstacles, the flying robot is automatically hold back by giving the "nick"-value a negative "impulse".

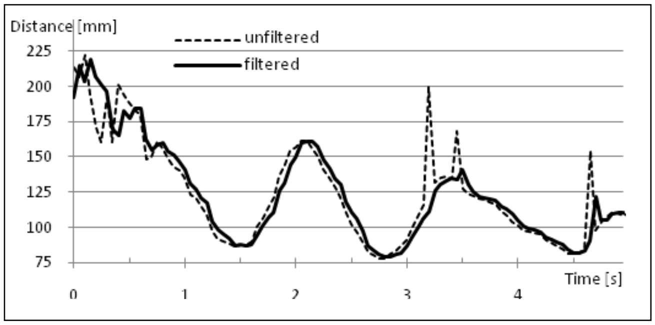

Figure 6. Filter performance with data from the ultrasonic distance rangers during flight

In order to emphasize edges, the image noise is suppressed by convoluting the picture with a discrete approximation of a Gaussian mask using δ=1,3 px.

By applying the Sobel operator in both x- and y-directions to the image, horizontal and vertical brightness gradients are detected, allowing to evaluate the slope of a potential edge passing through each pixel.

In order to be able to distinguish salient edges the Euclidian norm of both previously obtained gradients is calculated. In practice, the following approximation is used to reduce the computing cost, with g_x being the gradient in the x-direction and g_y the gradient in the y-direction:

$$G(x,y) = |\, g_x(x,y)| + |\, g_y(x,y)| \tag{3}$$

The edge detection is completed by the elimination of edges that are wider than one pixel. This is done by analyzing edge strengths and eliminating edges with insufficient strength. This last step yields an array of points representing the edges of the original picture, provided that the operators and threshold values were correctly chosen.

After the Canny algorithm is applied, the detected edges must be translated to the most salient straight lines in the picture. In order to do this a variation of the Hough-Transform, called the Kernel-based Hough Transform (KHT) [18] is used. This procedure allows robust real-time detection of parametrizable straight lines in edge pictures.

At first a "Hough-space" is defined, using the parameters of the straight line as axes. Here we use the straight line's angle φ and the Euclidian distance r to the origin.

Then the points of the detected edges are added to the Hough-space in the form of a line for each pixel of the original picture. Once this is done, the Hough-space can be analyzed to find intersections of the lines, which show the parameters r, φ of the salient straight lines in the original picture. The KHT simplifies this step by ignoring improbable lines before this analysis, thereby greatly reducing computing costs.

After the most significant line has been found, this information can be used as input for the height control, which uses a PID controller to continually adapt the throttle value. An example for the application of this camera based height control could be flying along a window edge.

VI. Flight Testing

Several indoor tests were performed so as to substantiate that the presented UAV is capable of exerting a specific force on a wall. These tests were conducted without the use of the control loops presented in section V (b). The microcontroller was programmed so as to allow remote activation of the horizontal propeller and speed variation using the ground station.

First of all, the stability of the UAV during wall contact and physical interaction was verified. To do this, the UAV was positioned close to the wall. Then the horizontal propeller was activated and the UAV came into contact with the wall. During wall contact the horizontal propeller's speed was set to the desired value. Hereby the force was measured using a force sensor mounted at the front of the quadrotor system. Fig. 7 shows the stable exertion of force to a wall during a representative flight. Other tests with contact times of more than two minutes were also conducted.

The current model was able to constantly generate a maximum force of 5 N while hovering. Using a 24 Wh accumulator and disabling the horizontal propeller leads to a flight time of approx. six minutes for the prototype. When the horizontal propeller is activated, the flight time is reduced by up to 50%, depending on the rotor speed. The weight of the UAV totals at 1.4 kg with an additional possible payload reaching up to 200 g. Ascension speeds of 2 m/s and horizontal speeds of 4 m/s are possible.

To prepare for the camera based throttle control, flight tests with the camera were conducted. The camera provided pictures at a frame rate of 15 fps. Using the image processing software the most salient edges were detected nearly in real time. Also the measurements from the ultrasonic rangers could be simultaneously sent to the ground station with a frequency of 8 Hz.

Videos of some flight tests can be downloaded from the following website:

http://www.ipek.uni-karlsruhe.de/quadrokopter

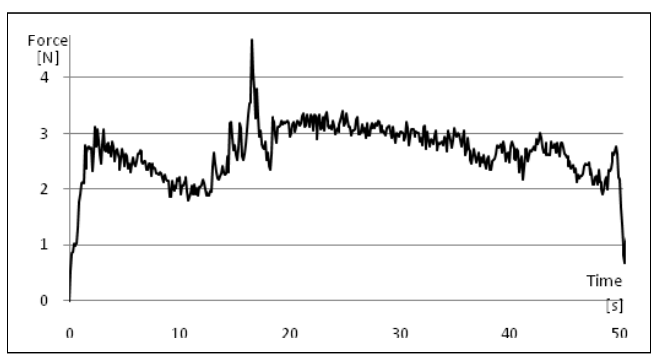

Figure 7. Force measurement during a wall contact of 50 seconds with a desired force value of three Newton

VII. Future Work

The feasibility of our project could be clearly shown using the available hard- and software. In the future the performance of the system has yet to be improved in the following fields:

The total weight of the UAV will be reduced so as to allow longer flight time or a higher payload. In order to do this an optimized CFRP-frame will replace the current frame. Constructive changes should ensure that lateral movement becomes easily possible during the exertion of a force.

To allow greater forces to be applied, the horizontal propeller will be driven by a brushless DC motor. The use of this motor type will also save weight.

The software is to be improved so as to enable enhanced semi- or fully automatic flights. The control loops presented in section V will be fully implemented and an expansion of the current sensor concept should allow a better detection of the UAV's environment. This in turn should enable the control loop to use detailed information on the environment for more precise control. A control of the applied force by using the data from the force sensors should also become possible. The object detection using the camera will be enhanced so as to allow autonomous flights based on the camera's data.

VIII. Conclusion

We were able to demonstrate that a flying robot can be rendered capable of executing physical tasks in elevated places while hovering stably. We showed a small and relatively light design which allows reaching target objects quickly. The prototype is capable of carrying a payload of 200 g while flying continuously for 6 minutes. The results of the flight tests demonstrate that flight stability can be maintained while applying a horizontal force of 5 N to a surface. Payload, flight time and applied force can be significantly improved by an increased use of lightweight materials as well as higher class batteries and motors. In combination with the camera-based control architecture, this approach offers a large potential for various applications which might be expanded even more by adding sensors to the system.

Such a flying robot may be employed for many other interesting tasks besides cleaning. These include connecting/disconnecting objects in high places, surfaces treatments like painting, polishing or sanding, transportation tasks, as well as pest elimination (e.g. destroying a vespiary in high places). Rescue operations could be supported when searching for endangered persons at sea or in the mountains (e.g. after avalanches), small rescue kits or markers to point out the position of a victim could be dropped from the UAV.

Further development is necessary before the functions described above can be realized, but applying force to a surface using a flying robot is a first, yet important step into this direction and an absolute prerequisite for realizing more complex applications in the future.

References

[1] N. Elkmann, M. Lucke, T. Krüger, D. Kunst, T. Stürze, "Kinematics and sensor and control systems of the fully automated facade cleaning robot SIRIUSc for Fraunhofer headquarters in Munich," in Field and Service Robotics, Volume 42/2008, Springer Berlin/Heidelberg, pp. 505-512, 2008.

[2] W. Fischer, F. Tache, R. Siegwart, "Magnetic wall climbing robot for thin surfaces with specific obstacles," Proc. of the Int. Conf. on Field and Service Robotics (FSR 2007), Chamonix, France, 2007.

[3] L. P. Kalra, W. Shen, J. Gu, "A wall climbing robotic system for non-destructive inspection of above ground tanks," Proc. IEEE CCECE/CCGEI, Ottawa, Canada, pp. 402-405, May 2006.

[4] H. Zhang, J. Zhang, W. Wang, R. Liu, G. Zong, "Sky Cleaner – a real pneumatic climbing robot for glass-wall cleaning," in IEEE Robotic & Automation Magazine, Vol.13, No.1, pp. 32-41, 2006.

[5] Z. Yanzeng, S. Hao, W. Yan, "Wall-climbing robot with negative pressure sucker used for cleaning work," in High Technology Letters 5, pp. 85-88, 1999.

[6] J. Xiao, A. Calle, A. Sadegh, M. Elliot, "Modular wall climbing robots with transition capability," Proc. of IEEE International Conference on Robotics and Biomimetics, pp. 246–250, 2005.

[7] X. Chen, M. Wager, M. Nayyerloo, W. Wang, J. G. Chase, "A novel wall climbing robot based on Bernoulli effect," IEEE/ASME Int. Conf. on Mechtronic and Embedded Systems and Applications (MESA 2008), Beijing, China, 2008.

[8] H. Prahlad, R. Pelrine, S. Stanford, J. Marlow, R. Kornbluh, "Electroadhesive robots—wall-climbing robots enabled by a novel, robust, and electrically controllable adhesion technology," Proc. of IEEE Int. Conf. on Robotics and Automation, 2008.

[9] O. Unver, A. Uneri, A. Aydemir, M. Sitti, "Geckobot: A gecko inspired climbing robot using elastomer adhesives," Proc. of IEEE Int. Conf. on Robotics and Automation, pp. 2329–2335, 2006.

[10] V. Remuss, M. Musial, G. Hommel, "MARVIN—an autonomous flying robot—based on mass market," IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, IROS, pp. 23-28, 2002.

[11] F. Adolf, F. Andert, S. Lorenz, L. Goormann, J. Dittrich, "An unmanned helicopter for autonomous flights in urban terrain," in Advances in Robotics Research, Springer, Berlin/Heidelberg, pp. 275-285, 2009.

[12] S. Scherer, S. Singh, L. Chamberlain, S. Saripalli, "Flying fast and low among obstacles," IEEE International Conference on Robotics and Automation, Rome, Italy, April 2007.

[13] O. Amidi, T. Kanade and R. Miller, "Vision-based autonomous helicopter research at Carnegie Mellon Robotics Institute," Proceedings of Heli Japan '98, Gifu, Japan, 1998.

[14] B. Bethke, J. How, J. Vian, "Group health management of UAV teams with applications to persistent surveillance," American Control Conference, Seattle, WA, USA, 2008.

[15] A. Nishi, H. Miyagi, "Mechanism and control of propeller type wall-climbing robot," in Advanced Robotic Systems and the Real World, IROS '94. Proceedings of the IEEE/RSJ/GI International Conference on Intelligent Robots and Systems, pp. 1724–1729, 1994.

[16] H. Buss, I. Busker, "Mikrokopter," website of a quadrotor project, http://www.mikrokopter.de, January 2010.

[17] J. F. Canny, "A computational approach to edge detection," IEEE Trans. Pattern Analysis and Machine Intelligence, 1986.

[18] L. A. F. Fernandes, M. M. Oliveira, "Real-time line detection through an improved Hough transform voting scheme," Pattern Recognition (PR), Elsevier, pp. 299-314, 2008.