Design of an optical flow sensor for off-road robot application

Bachelor Thesis

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1 Preface

This bachelor thesis was realized at the Autonomous System Lab (ASL) at ETH Zürich in the spring semester 2009. I would like to thank Mark Höpflinger and Ambroise Krebs for their assistance during the whole project. I want also to thank Yang Yu for his help in reading out the position data and the image from the mouse sensor.

2 Abstract

This paper concerns the evaluation and realization of an optical sensor from a standard computer mouse used as a device to recognize the movement of a robot in unstructured outdoor terrain.

At the beginning some general theory about the working principle of optical sensors is given. In the next part several solutions for a suitable optic are presented with focus on telecentric lenses and different autofocus systems, where an optical system with a liquid lens turned out to be the best solution. The following chapter contains the application of a fixed lens. In the last chapter the setup of a prototype of the sensor, the readout of the image from the sensor, the calibration, the buildup of the test bed and the results of measurements on different surfaces are presented.
3 Introduction

3.1 Motivation

For autonomous robot navigation, the exact knowledge of the actual position is very important. This makes it possible for the robots to navigate, do specific tasks or find its target and that allows the robots to act completely autonomous.

To determine the actual position or displacement, different solutions are possible. Today, robots are usually equipped with a GPS sensor that allows determining the absolute position of the robot all over the world. Unfortunately, the accuracy of GPS is not very high and it is not possible to use the data for exact localization and furthermore, in buildings, in urban areas or even on other planets, GPS is not available. Another option is to find out the actual position by using gyroscopes and wheel encoders. For short distances, this method yields good results. But due to slippage it cannot be used for long distances because the error is unbounded. Another possibility is to use a stereo camera for localization. In this approach, images from the camera are compared with the goal to find conspicuous points in both images. That allows calculating the movement of the robot in the time between the two images. This makes the localization completely independent from slippage, inaccurate GPS and other noise. But the method is complicated, quite expensive and needs a lot of computation power. Another often used and quite accurate method works with laser rangefinders, which provide 2-dimensional or even 3D scan matches.

In this thesis, an approach is presented that uses a standard optical flow sensor from a commercial optical mouse with a suitable optic looking at the floor. The measurement of this sensor is not distorted by slippage as with wheel encounters and it works also where GPS is not available, for example on another planet or in buildings. Furthermore, the components are quite cheap and the computation can be done by a simple microchip. The components are very small and can be implemented in most robots.

This work is a continuity of a former bachelor thesis, realized in 2008 by Dieter Flubacher and entitled: “Characterization of an optical flow sensor for off-road robot application”. [1]

3.2 Project tasks

- Research to find possible solutions especially with autofocus and telecentric lenses
- Evaluate solutions for the CRAB rover (slow with varying ground clearance) and the Boogar (fast with small ground clearance)
- Realization of a prototype for the CRAB rover
- Test and characterization
4 Theory

The goal of this thesis is to design and build an optical-flow sensor to estimate the movement of a robot, navigating in rough terrain. The idea is to use a standard optical-flow sensor as used in computer mouses looking at the floor. These sensors take up to several thousand pictures per second and by comparing consecutive images, the actual movement of the sensor can be calculated. These mouse sensors are usually dimensioned for a very small and constant distance between the sensor and the measured surface and therefore, an appropriate optic has to be created that the sensor also works on larger and varying distances to the ground. Furthermore, a suitable illumination is needed because the sensors need a bright illuminated ground to receive viable and useful data. For the optic, several approaches are possible. The different possibilities include fix lenses, an autofocus system or telecentric optic.

4.1 Optical mouse sensors

In optical mouses, a LED or a laser illuminates the surface and the reflection is detected by a CMOS sensor. This sensor compares successive images and an optical flow algorithm calculates the displacement in the two directions on the surface. The architecture of an optical mouse is shown in Figure 1. Rotation cannot be detected and therefore one mouse sensor is not sufficient for real robot application.

![Figure 1: Architecture of an optical mouse sensor with LED illumination](image1)

![Figure 2: Mouse sensor ADNS-7050](image2)
For illumination, mouse sensors use a LED or a laser diode. Modern mouse sensors usually use a laser diode which works on more surfaces as specified by the manufacturer. For the application on robots, where the height is larger and variable, a laser as illumination does not work because the beam is not wide enough to illuminate a sufficient large area. Therefore LED illumination was used.

Today, mouse sensors have frame rates up to 6400 frames per second. The resolution of the image is very small; usually it is only between 16x16 pixels and 30x30 pixels. Due to mass production, these sensors are very cheap. Usually, they cost only a few Swiss francs.

In this thesis I used an Avago ADNS-7050 (Figure 2) with a resolution of 22x22 pixels and with its maximum frame rate, a maximum velocity of about 0.5 m/s is possible. \cite{2}\cite{3}\cite{4} The smallest displacement that theoretically can be registered in normal mouse operation is 0.0635 mm which can be calculated from the resolution of the sensor: \[ \frac{2}{800 \text{ dpi}} \times 25.4 \text{ mm/in} = 0.0635 \text{ mm.} \] For larger distances to the ground, this value can be much higher because of the smaller magnification. The sensor I used is taken from a Logitech RX1000 mouse because it was difficult to buy single sensors.

4.2 Optic

4.2.1 Fix lenses

One possibility to realize the optic is to take fix lenses and therefore sharp images are obtained only at a single distance to the floor. Combined with a range sensor, the motion and therefore the displacement can be determined. Due to images out of focus and the inaccuracy of the range sensor on rough terrain, some errors are unavoidable. This approach with fix lenses has been discussed in a previous bachelor thesis by Dieter Flubacher. \cite{1}\cite{5}

4.2.2 Autofocus

To implement an autofocus system, there are generally two possibilities: an active and a passive autofocus. The passive autofocus analyses the captured image tries to find the sharpest focus. This method is not optimal for this application, because the mouse sensor has an internal image processor which is not able to analyze the sharpness and an external processor which analyses that would be another additional effort. This would destroy the advantage of the simplicity of the displacement measurement with a mouse sensor compared with a normal camera. Another problem would be that it takes too long to read out the image. The active autofocus uses an external range sensor to measure the clearance and give this information to the autofocus controller. The advantage is that the distance information can also be used for calculating the scaling factor to determine the actual displacement with the output of the mouse sensor. That the signal of the distance sensor contains some noise and that the autofocus has to be calibrated are small disadvantages.

There are many possibilities for autofocus modules. Conventionally, they work with standard electromagnetic actuators that move a lens or several lenses. This method is quite simple but the
mechanic is susceptible to error and to dirt and the focusing is not very fast. Here I present two new approaches which are smaller, faster, more energy-efficient and less delicate than the conventional actuators: liquid lenses and piezo autofocus modules.

**Liquid lenses**

A new technique to realize an autofocus is the liquid lens. They consist of two liquids, usually water with some additives and oil, between two glasses in a short conical tube. The two fluids have the same density but different refractive index so that the interface of the liquids shapes a variable-focus lens. Depending on the voltage applied, the radius of the boundary between the liquids changes its shape and therefore forming very smooth lenses with different focal lengths. It is possible to focus from 5 cm to infinity. Usually, the liquid lens is combined with fixed lenses to build an autofocus. The working principle is shown in Figure 3 and Figure 4.

The main advantage of this technology is that these lenses have no moving parts and are therefore robust, durable and shock-resistant. Another advantage is that these lenses can be designed very small and that they have very short response times. Due to the physical properties of the liquids, the lens can operate between -20 °C and +60 °C. The power consumption is typically less than 0.1 mW and the electrical properties of a liquid lens are very similar to those of a capacitor, where the water functions as conductor, the oil as insulator. [6]

Focusing can be done in two ways. The first common way is to directly control the focus as it is done with usual autofocus systems. Another way is to apply a fast oscillation to the lens that the camera sensor registers all images. An algorithm then takes automatically the sharpest images. [7]
To control the liquid lens, a driver board is needed which can be controlled e.g. over an I\textsuperscript{2}C interface from a microprocessor. [8] The driver board outputs the needed voltage for the liquid lens which is between 0 and 60 Volts.

The cost of a liquid lens depends largely on the ordered amount. Bought singly, they are expensive but in large amounts, they are very cheap. Liquid lenses will soon be sold in a webcam and in future it is planned to integrate them in cell phones, webcams and other devices with small cameras.

Piezo autofocus modules

Piezo autofocus modules (Figure 6 and Figure 7) use a mechanical optic actuated by a piezo element. This allows a very compact design and low energy consumption. The small size and the piezo technology make the autofocus process very fast. Usually, these modules are used in cell phones or small cameras for security and surveillance purposes. [9]

The control of the piezo autofocus is quite challenging because to set the correct focus, the image data from the sensor is needed. An algorithm analyses continuously the image on the sensor and sends information to a controller, which changes the focus until the algorithm recognizes that the image is sharp. This would need extra hardware and software and there could be a problem for the algorithm to find the optimal focus because the image from the mouse sensor is very small, in our

Figure 5: Liquid Lens Arctic 416

Figure 6: Piezo autofocus module front view

Figure 7: Autofocus module side view
case 22 x 22 pixels. Furthermore, the readout of the image is slow and it would destroy the advantage of the mouse sensor, as described above.

As with the liquid lens, a driver board is needed to generate the needed voltage to control the piezo autofocus module.

### 4.2.3 Telecentric lenses

In contrast to conventional lenses, telecentric lenses have a constant magnification of objects independent from their distance. The ray of light form the object runs parallel to the objective, as shown in Figure 8 and Figure 9. A telecentric lens projects only a cylindrical space in front of the objective on the sensor or film. That means that only objects smaller than the area of the lens can be imaged completely. Another characteristic is that parallel lines stay parallel independent from the perspective. To assure that only the parallel rays can pass the optics, it contains an aperture. Unfortunately, that limits the amount of light that can pass through the lens. Therefore longer exposure time or brighter illumination of the object is needed compared with conventional lenses. As conventional lenses, normal object-space telecentric lenses have only one optimal focal distance which is quite small, usually about ± 1 mm. Objects with distances out of the focal distance are not sharp. For expensive double telecentric objectives the depth of field is larger but they are heavier and bigger. [10][11]

Usually, telecentric lenses are delivered with a standard C-mount as used in most common professional cameras. The thread is 1 inch (25.4 mm) in diameter with 32 threads per inch and the focal distance is 0.69 inch (17.526 mm). A disadvantage of telecentric lens is that they are quite expensive, even if they are bought in large amounts. This means that each sensor is expensive even if they are produced in mass production and therefore it would not be implemented in most robots.

Another option is to take special aspheric lenses as used from a team of Tohoku University in Japan [12]. They presented a similar approach but with a normal camera instead of a mouse sensor. After a lot of trial and error they reached good results. Aspheric lenses focus parallel light beams in one focal point and function therefore almost like telecentric objectives. The disadvantage is that these aspheric lenses are quite large and because of their special form, they are usually custom-made devices.

![Figure 8: commercial double-telecentric lens system: telecentric on both object and image side](image.png)

![Figure 9: left: conventional lens; right: telecentric lens](image.png)
4.3 Illumination

For proper results, mouse sensors need sufficient illumination. In optical mouses, this is usually done by a red LED or in newer ones with a power saving infrared laser diode. Due to the small distance of some millimeters between the mouse and the table, enough reflected light reaches the mouse sensor. Light disturbances around the mouse are shielded by the mouse itself and have therefore no influence on the measurement.

In applications for outdoor robots, the clearance to the ground is much larger. This means that the intensity of the illumination has to be increased. The ground has to be bright enough that even if it is 30 cm below the sensor, the movement can still be recognized. Figure 11 shows that mouse sensors built for infrared laser diode also work with red LEDs. This is essential for this project. The illumination cannot be done with lasers because their beam is extremely focused but the sensor needs a big enough area which is illuminated. To achieve this, the illumination is done by several ultrabright LEDs positioned in a circle around the mouse sensor (Figure 10). The circle around the sensor avoids unwanted changing shadows from objects on the ground and the brightest area is exactly below the mouse sensor, independent from the height.

![Figure 10: Optic in the center and LED-circle for illumination](image1)

![Figure 11: Relative responsivity of the used mouse sensor Avago ADNS-7050](image2)
5 Evaluation

Optical flow sensors can be useful in several applications with different requirements. In this thesis, solutions for two possible applications for autonomous robots are evaluated. On the one hand the very fast boogar, on the other hand the CRAB, a slow rover driving over rough terrain.

5.1 Boogar

For the boogar (Figure 12) it is important to have a very fast sensor because the boogar is constructed for a maximal speed up to 60 km/h. That means that the sensor needs very high sampling rate. Less important in this application is the varying clearance to the ground because it can be assumed to be almost constant in the range of some centimeter.

The fastest mouse sensors can process movements of about 1 m/s in normal mouse application. Due to the larger distance to the ground and therefore larger field of view in the boogar application, higher velocities are possible but speeds up to 50 km/h are not measurable with this approach. Another problem would be that the used distance sensor is too slow (25 Hz) [13].

5.2 CRAB

The CRAB (Figure 13) is a slow and versatile rover for unstructured outdoor terrain and it can be driven with a maximum speed of 0.1 m/s. Its ground clearance is about 20 cm but due to rough and uneven terrain, this clearance can vary between 5 cm and 30 cm.

For this application, the approach with the mouse sensor is very suitable. The slow velocities allow exact measurements of the movement and with an appropriate optic, the problem of the varying clearance is solvable. The exact positioning is essential for the CRAB for navigating autonomous on other planets where no GPS is available.
5.3 Decision Matrix

To find the suitable solution for this project, a decision-matrix was created (Table 1). The most important and therefore highest weighted criterions are accuracy, reliability and complexity. It can be seen that the liquid lens is the best solution. This is mainly because of the expected accuracy and the fact, that this solution is very small and light. The piezo autofocus system is worse because there, more complex controllers are needed and that makes it much more complicated and prone to error. Telecentric lenses have the disadvantage that the depth of field is very small, usually about 1 mm. Double telecentric objectives have a larger depth of field but are much larger, heavier and much more expensive. The fix lens is the worst solution because of its inaccuracy.

The energy consumption considers the control of the autofocus, which is usually in the region of some milliwatt, as well as the needed illumination, which is the highest for the telecentric lens and the most energy-intensive part for all solutions.

Most valuations are determined with datasheets and general information about the different products. When no exact information was available, the values for the valuation were estimated.

Table 1: Decision Matrix

<table>
<thead>
<tr>
<th>Criterion</th>
<th>weight</th>
<th>%</th>
<th>Telecentric lens</th>
<th>Liquid autofocus Varioptic Arctic 416</th>
<th>Piezo autofocus miniswys SMIA AF 85</th>
<th>Fix focus</th>
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<td>1</td>
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6 Application

For the solution with the liquid lens, an appropriate optic for focusing has to be designed and a distance sensor has to be implemented.

6.1 Optic

To get a sharp image on the mouse sensor, the focal distance of the lens has to be adjusted correctly. This can be calculated with the thin lens formula

\[ \frac{1}{f} = \frac{1}{g} + \frac{1}{b} \]

where \( g \) is the clearance to the object given from the distance sensor, \( b \) is the distance from the lens to the mouse sensor which is typically about 1.5 mm with liquid lenses and \( f \) is the focal length that has to be set at the lens (Figure 14). For liquid lenses, \( f \) can be set from less than 5 cm to infinity.

The time variable focal length \( f_{(t)} \) can therefore be found as

\[ f_{(t)} = \frac{1}{\frac{1}{g_{(t)}} + \frac{1}{b}} \]

where \( f_{(t)} \) is proportional to the voltage \( u_{(t)} \) applied to the liquid lens.

\[ u_{(t)} = c \cdot f_{(t)} \]

The voltage \( u_{(t)} \) is provided by a driver board and depends on the distance to the ground measured by the distance sensor.

![Thin lens diagram](Figure 14: Thin lens)
6.2 Distance Sensor

The measured clearance from the distance sensor is needed for two tasks. First, the controller needs this information to adjust the autofocus that the floor is projected sharp on the sensor. Second, the scaling factor to determine the real displacement can only be calculated if the clearance is known.

For this task, a standard analog IR ($\lambda \approx 850\,\text{nm}$) distance sensor is taken which uses triangular measurement to determine the distance, the Sharp GP2D120 [13]. Its range is from 4 cm to 30 cm which matches pretty well the requirements.

In the working range of the sensor, the analog voltage output is almost straight proportional to the inverse of the distance. With a linear approach an accuracy of about $\pm 1\,\text{mm}$ was achieved which is sufficient for this application. On inappropriate surfaces, for example if they are very glossy or transparent, the error can increase or the measurement can be completely impossible. A linear correlation was found by measuring the output voltage and the distance at several points and afterwards fitting a suitable curve into the measured points.

The typical response time of the IR distance sensor is 39 ms. This allows a maximum sampling rate of about 25 Hz which is several times slower than the mouse sensor. Additionally, the readout and the evaluation of the analog input from the microprocessor add a delay. Because of this, the distance sensor is readout less frequent than the mouse sensor. Due to some noise, the output signal has to be filtered to achieve better results. This adds another delay but all delays are very small with respect to the slow movement of the robot. Therefore the delays cause no problem for this application.

6.3 Setup

For a working prototype, all components are controlled with a microprocessor-board. The distance sensor is connected to the analog input port at the board. The mouse sensor uses an SPI interface to communicate with the board. The driver for the liquid lens has also to be connected to the board and controlled over an I$^2$C interface. The output of the microchip-board is a serial-interface which transmits the data, in this case the actual displacement and height, to a computer. With this prototype setup, it is possible to evaluate the accuracy of this approach. The setup is shown in Figure 15. Due to late delivery, too little time at the end and problems with the readout of the image, the liquid lens was not integrated and tested in this project and a fixed optic was used.

An important fact is that for this prototype setup, only universal standard components are used. To readout the data, a normal serial interface can be used. The calculation and the formatting of the output signal are done in the microchip. The computer just displays what it receives from its serial port. This allows using the built sensor setup independently from any particular operating system or special software.

Alternatively, the displacement data can be directly used for further processes in a robot, for example in navigation tasks. Due to the universal setup, this can also be done without needing a computer to transform the data.
6.4 Sensor arrangement

Standard mouse sensors can measure the movement in two directions. The output of such a sensor is the change in position in the x-direction and y-direction. This implies that a rotation is not recognized. To consider rotations as well as the movements along the x-axis and y-axis, at least two sensors are needed. More than two sensors can be used to get redundant information and therefore to improve the robustness and the accuracy of the system.

This implementation is not part of this thesis. But with two equivalent sensors as proposed or in combination with other sensors and some calculation, it can be implemented on a robot.
7 Testing

For testing, a microprocessor-board (ASL, dsPic33) was used. The liquid lens is not used in a first step and therefore the driver board for the liquid lens has not to be connected. As an optic, a fixed lens is mounted on the mouse sensor. As the output of the microprocessor-board the serial-interface which transmits the data to a computer is used. This output is in a first step the captured image (see next chapter). With this prototype setup, it is possible to find the optimal position and distance of the lens in relation to the mouse sensor. The test setup with the fixed lens can be seen in Figure 16.

![Figure 16: Mouse sensor (top) and fixed optic (bottom) on a mounting, without illumination](image16)

![Figure 17: Test setup for image capturing with adjustable height above ground](image17)

7.1 Image capture

To see if the image on the mouse sensor is sharp, the image was read out. This turned out to be very difficult. First, it is very hard to get the data from every pixel of the sensor because the pixels can only read out one at the time and they are only updated if the sensor recognizes a movement. This means, that to get an unmoved picture, the readout takes quite a long time. For each pixel, the microchip has to wait until there is a slight change in illumination or a small movement. Another problem was that with the standard optic from the optical mouse, no meaningful image appeared. The image was always a gray area without any contours. This is probably due to the very large magnification and the automatic adjustment of the contrast. With a lot of trial and error, a fixed optic from a small camera was found. It allowed making useful images from most surfaces. The fixed optic was used because it is almost impossible to find optimal focus distance and the correct position...
to directly attach the liquid lens to the mouse sensor. The focused image has to fit very exactly in a small hole to reach the photo sensor in the mouse sensor. To find this correct position was very challenging even with the fixed optic. In the next step, the liquid lens can be attached to the fixed optic or the fixed optic can be completely replaced by the liquid lens.

The read out image also allowed finding the optimal illumination. This was realized by a circle of several ultra-bright red LEDs around the optic gleaming at the area on the ground which is captured by the sensor. The power supply of the illumination is done external and therefore independent form the sensor. It showed that a constant illumination works for all needed distances due to the automatic adjustment of the contrast and brightness in the sensor. On some surfaces it even works without special illumination.

To capture the images, a test-setup (Figure 17) was designed allowing the adjustment of the distance to the ground easily. For this, a stand of a drill press (Dremel Workstation 220) was used. Its height can be adjusted by moving a lever. With this setup, it was possible to get sharp and unmoved images from different distances.

With the read out images, for each distance a suitable voltage to control the liquid lens can be found. To achieve this, for several input voltages for the liquid lens the corresponding distance can be determined to get a sharp image. This is quite difficult because on a 22 x 22 pixel image, it is very hard to find the sharpest image. But for the displacement measurement, the images have not to be extremely sharp. After the measurements, it is possible to find a correlation between the distance to the ground and the corresponding voltage at the lens. As mentioned above, the integration and tests with the liquid lens have not been done in this project.

Some images made with this setup (Figure 17) can be seen in Figure 18. Note that the images are mirror-inverted because the standard lens built in optical mouses flips the image whereas the lens used for this project projects the image without flipping. This is no problem but the signs of the displacement have to be changed.

Figure 18: Frame captures read out from the mouse sensor
7.2 Calibration and displacement measurement

For the calibration of the distance sensor, several measurements from different distances were taken to find the relation between the output voltage and the real distance. A fit of the points yielded an almost linear relation between the analog voltage output and the inverse number of distance.

At the end, the displacement values of the mouse sensor had to be adapted because of the variable distance to the ground. The calculated x- and y-values are only valid for the standard distance of the sensor built in the mouse. For larger distances, these values have to be multiplied by a scaling factor depending on the actual height. This scaling factor was also found by displacement measurements at different heights and on different surfaces. The results can be found in the following chapters.

7.3 Test bed

For evaluating the sensor, a test bed (Haase Cut 2005 L[14]) as shown in Figure 19 was used. In comparison with a test on the real robot, the test bed allows getting meaningful and repeatable results. With a standardized ground, several measurements can be done and evaluated. The test bed allows moving the sensor with different velocities and at different heights over a given distance. With the used test bed movements in one direction as well as in the height are possible. The maximum horizontal driving distance is 600 mm and vertically, movements of about 80 mm are possible. With this, the reality can be simulated very well. Rotations are not possible with the used test bed but that is no problem due to the fact that only one sensor cannot recognize rotations.

The test bed is controlled with software (EMC2: Enhanced Motor Controller for Linux[15]) that allows driving the sensor with a constant velocity exactly to a certain point which was used for most of the tests. It is also possible to program a sequence of movements and therefore driving almost every shape. This option was used for the latest tests where a triangle and sawtooth wave were programmed. A screenshot of the user interface is shown in Figure 20.
7.4 Experiments

In the experiments, the sensor is tested on several surfaces and with different velocities and the accuracy is evaluated on each test scenario. With this information, it is possible to make statements, for which situation the sensor is very accurate and in which cases the accuracy is poor. This allows evaluating for which robot application the sensor is suitable.

For all measurements I used the LEDs for illumination. The real displacement on the test bed was always set to 500 mm which is almost the maximal usable length of the test bed. The velocity was set to 1200 mm/min except for some tests to find the minimal possible velocity.

The evaluation of the results was done by Matlab where a program which reads out the displacement and distance information of the log files from the measurements was written. This allows making plots of any combination of the data in 2D or also in 3D. The most important ones are the x-z-plane and x(t). The x-z-plane shows the distance to the ground for each point x on the movement. In the x(t) plot, the movement of x depending on the time can be seen. Because the sensor moved at a constant velocity on the test bed, this function should be a straight line with a constant slope, except at the sawtooth wave, where the movement in the x-direction is not constant.
7.4.1 Constant height

The first displacement measurements were taken on flat surface with a constant height. In robot application, this is the case for indoor robots or outdoor robots driving on even ground, for example on a street. For this task, the autofocus is not necessary due to constant clearance to the ground. The distance sensor has not been used for the calculation either. It was only used to find the distance from the mouse sensor to the ground and to calculate the scaling factor.

The measurements with the constant height are used to calibrate the sensor. Because the registered displacement depends on the height, a scaling factor has to be added for each height. Each scaling factor was evaluated by making some tests counting the movement steps of the mouse sensor at a specific height. The average of these values can be used to find the scaling factor for this specific height. After that, some measurements at this height were taken with the scaling factor added in the code. The output is the displacement in millimeters.

Because of the very flat and even ground with almost no structure, it was probable that the sensor has difficulties to register the movement and the ground was covered with newspapers at tests 1-12. Surprisingly, the sensor has also no problem with the glossy and very dark surface of the test bed. Because of that, measurements on that ground were also done.

**Measurement with newspaper**

As mentioned above, the first twelve tests were made with newspaper covering the ground (see Figure 19). Due to some wrinkles in the newspaper the surface was not completely even. Therefore the distance to the ground varied about ± 5 mm but that did not influence the measurement appreciable. The results can be seen in Table 2 and in Figure 21.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Δx real [mm]</th>
<th>Δx measured [mm]</th>
<th>Absolute error [mm]</th>
<th>Relative error [%]</th>
<th>Height [mm]</th>
<th>Scaling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500</td>
<td>420</td>
<td>80</td>
<td>16</td>
<td>104</td>
<td>7.937</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>434</td>
<td>66</td>
<td>13.2</td>
<td>104</td>
<td>7.937</td>
</tr>
<tr>
<td>3</td>
<td>500</td>
<td>558</td>
<td>58</td>
<td>11.6</td>
<td>104</td>
<td>9.259</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>492</td>
<td>8</td>
<td>1.6</td>
<td>78</td>
<td>3.125</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>477</td>
<td>23</td>
<td>4.6</td>
<td>78</td>
<td>3.125</td>
</tr>
<tr>
<td>6</td>
<td>500</td>
<td>483</td>
<td>17</td>
<td>3.4</td>
<td>78</td>
<td>3.125</td>
</tr>
<tr>
<td>7</td>
<td>500</td>
<td>497</td>
<td>3</td>
<td>0.6</td>
<td>66</td>
<td>2.475</td>
</tr>
<tr>
<td>8</td>
<td>500</td>
<td>497</td>
<td>3</td>
<td>0.6</td>
<td>66</td>
<td>2.475</td>
</tr>
<tr>
<td>9</td>
<td>500</td>
<td>504</td>
<td>4</td>
<td>0.8</td>
<td>66</td>
<td>2.475</td>
</tr>
<tr>
<td>10</td>
<td>500</td>
<td>500</td>
<td>0</td>
<td>0</td>
<td>55</td>
<td>1.901</td>
</tr>
<tr>
<td>11</td>
<td>500</td>
<td>500</td>
<td>0</td>
<td>0</td>
<td>55</td>
<td>1.901</td>
</tr>
<tr>
<td>12</td>
<td>500</td>
<td>492</td>
<td>8</td>
<td>1.6</td>
<td>55</td>
<td>1.901</td>
</tr>
</tbody>
</table>
It can be seen, that the results are pretty good for small heights (Error below 5% for heights between 55 mm and 78 mm). For heights larger than 100 mm, the error is growing. This happens because the measured displacement from the sensor gets smaller with increasing height and the sensor has difficulties to detect very slow movements. This phenomenon is examined in a following chapter and the correlation between the distance and the error can be seen in Figure 24.

**Measurement without newspaper**

The next tests were made without newspaper covering the ground. The ground of the test bed is a black and polished board which turned out to be no problem. The test bed is very precise and there is no variance in the distance between sensor and ground. The results of these tests can be seen in Table 3 and Figure 22.

**Table 3: Flat surface of the test bed, velocity: 1200 mm/min**

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Δx real [mm]</th>
<th>Δx measured [mm]</th>
<th>Absolute error [mm]</th>
<th>Relative error [%]</th>
<th>Height [mm]</th>
<th>Scaling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>500</td>
<td>426</td>
<td>74</td>
<td>14.8</td>
<td>148</td>
<td>14.706</td>
</tr>
<tr>
<td>14</td>
<td>500</td>
<td>470</td>
<td>30</td>
<td>6</td>
<td>148</td>
<td>14.706</td>
</tr>
<tr>
<td>15</td>
<td>500</td>
<td>485</td>
<td>15</td>
<td>3</td>
<td>148</td>
<td>14.706</td>
</tr>
<tr>
<td>16</td>
<td>500</td>
<td>502</td>
<td>2</td>
<td>0.4</td>
<td>74</td>
<td>2.551</td>
</tr>
<tr>
<td>17</td>
<td>500</td>
<td>499</td>
<td>1</td>
<td>0.2</td>
<td>74</td>
<td>2.551</td>
</tr>
<tr>
<td>18</td>
<td>500</td>
<td>499</td>
<td>1</td>
<td>0.2</td>
<td>60</td>
<td>1.938</td>
</tr>
<tr>
<td>19</td>
<td>500</td>
<td>501</td>
<td>1</td>
<td>0.2</td>
<td>60</td>
<td>1.938</td>
</tr>
<tr>
<td>20</td>
<td>500</td>
<td>501</td>
<td>1</td>
<td>0.2</td>
<td>60</td>
<td>1.938</td>
</tr>
<tr>
<td>21</td>
<td>500</td>
<td>499</td>
<td>1</td>
<td>0.2</td>
<td>60</td>
<td>1.938</td>
</tr>
</tbody>
</table>
In this configuration there are also problems with larger distances to the ground. There, the errors are quite large (Error more than 5% for heights over 148 mm). But with smaller distances and by an optimized scaling factor, the error is always below 1%. That showed that the sensor is very precise for measurements on even surfaces if the height is between 40 mm and 110 mm and the velocity is not too slow (faster than 1000 mm/min). The relative error compared with the errors on newspaper on different heights is shown in Figure 24. The better results on the black surface than on newspaper are due to some problems on the white areas on the newspaper and due to improvements in the measurement method and more accurate determination of the scaling factor in the later measurements.

**Measurement with different velocities**

To determine the minimal speed some more measurements have been done which are shown in Table 4. The different velocities can be easily set at the test bed. I used a constant height of 60 mm for all measurements to get meaningful and comparable results. To get more accurate results, more measurements would be needed.

**Table 4: Flat surface of the test bed with different velocities, height: 60 mm**

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Δx real [mm]</th>
<th>Δx measured [mm]</th>
<th>Absolute error [mm]</th>
<th>Relative error [%]</th>
<th>Scaling factor [mm]</th>
<th>Speed [mm/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>500</td>
<td>302</td>
<td>198</td>
<td>39.6</td>
<td>1.938</td>
<td>600</td>
</tr>
<tr>
<td>23</td>
<td>500</td>
<td>434</td>
<td>66</td>
<td>13.2</td>
<td>1.938</td>
<td>800</td>
</tr>
<tr>
<td>24</td>
<td>500</td>
<td>476</td>
<td>24</td>
<td>4.8</td>
<td>1.938</td>
<td>1000</td>
</tr>
<tr>
<td>25</td>
<td>500</td>
<td>501</td>
<td>1</td>
<td>0.2</td>
<td>1.938</td>
<td>1200</td>
</tr>
</tbody>
</table>

It turned out that the error is larger than 5% if the velocity is lower than 1000 mm/min. This is probably due to the low resolution of the sensor or due to numerical problems. The results are shown in Figure 23. Unfortunately it is not possible to reach higher velocities than 1200 mm/min with the used test bed and therefore it was not possible to determine the maximal possible velocity.
7.4.2 Variable height

With the collected data from the previous measurements, a relation between the scaling factor and the height was found. The relation between the distance to the ground and the inverse scaling factor is almost linear. Therefore a linear formula to determine the scaling factor from a given distance was used. This allows making measurements on uneven surfaces or with changing heights of the test bed.

Uneven surface

In a first series of tests on uneven surfaces, wavy materials were used. As one test object, pink foam from packaging with small waves was taken (see Figure 26). This causes some problems because if the distance sensor and the mouse sensor do not point exactly at the same point, the scaling factor is wrong and the results are not accurate. Another problem is that the distance sensor is not very precise on the fluffy foam. To avoid these problems some larger waves with a newspaper were formed (see Figure 27). This setup allows much better results than the other one. The results from both tests with uneven surfaces are shown in Table 5 and the plots of the newspaper wave are shown in Figure 25.

Table 5: Uneven surface, velocity: 1200 mm/min

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Δx real [mm]</th>
<th>Δx measured [mm]</th>
<th>Absolute error [mm]</th>
<th>Relative error [%]</th>
<th>Height [mm]</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>500</td>
<td>551</td>
<td>51</td>
<td>10.2</td>
<td>80 to 117</td>
<td>pink foam wave</td>
</tr>
<tr>
<td>27</td>
<td>500</td>
<td>554</td>
<td>54</td>
<td>10.8</td>
<td>80 to 117</td>
<td>pink foam wave</td>
</tr>
<tr>
<td>28</td>
<td>500</td>
<td>510</td>
<td>10</td>
<td>2</td>
<td>45 to 95</td>
<td>newspaper waves</td>
</tr>
<tr>
<td>29</td>
<td>500</td>
<td>503</td>
<td>3</td>
<td>0.6</td>
<td>45 to 95</td>
<td>newspaper waves</td>
</tr>
<tr>
<td>30</td>
<td>500</td>
<td>514</td>
<td>14</td>
<td>2.8</td>
<td>45 to 95</td>
<td>newspaper waves</td>
</tr>
</tbody>
</table>
In a last series of tests, the ground is even as in the first tests but the height of the sensor is changed by the test bed. The test bed allows driving almost all possible trajectories. Some tests were done with simple rising height over the measurement distance and other with different waveforms like triangle and sawtooth. In Table 6 and in Figure 28 and Figure 29 the results of these measurements are shown.
Table 6: Change in height of the sensor, velocity: 1200 mm/min

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Δx real [mm]</th>
<th>Δx measured [mm]</th>
<th>Absolute error [mm]</th>
<th>Relative error [%]</th>
<th>Height [mm]</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>500</td>
<td>514</td>
<td>14</td>
<td>2.8</td>
<td>60</td>
<td>variable scale factor</td>
</tr>
<tr>
<td>32</td>
<td>500</td>
<td>517</td>
<td>17</td>
<td>3.4</td>
<td>60 -&gt; 110</td>
<td>rising height</td>
</tr>
<tr>
<td>33</td>
<td>500</td>
<td>522</td>
<td>22</td>
<td>4.4</td>
<td>60 -&gt; 110 -&gt; 60</td>
<td>rising and falling</td>
</tr>
<tr>
<td>34</td>
<td>500</td>
<td>490</td>
<td>10</td>
<td>2</td>
<td>63 to 101</td>
<td>sawtooth wave</td>
</tr>
<tr>
<td>35</td>
<td>500</td>
<td>499</td>
<td>1</td>
<td>0.2</td>
<td>63 to 101</td>
<td>sawtooth wave</td>
</tr>
<tr>
<td>36</td>
<td>500</td>
<td>515</td>
<td>15</td>
<td>3</td>
<td>63 to 101</td>
<td>triangle wave</td>
</tr>
<tr>
<td>37</td>
<td>500</td>
<td>498</td>
<td>2</td>
<td>0.4</td>
<td>63 to 101</td>
<td>triangle wave</td>
</tr>
</tbody>
</table>

Figure 28: Plots of the triangle wave. The straighter the line in the right plot, the better the measurement

Figure 29: Plots of the sawtooth wave. The horizontal lines in the right plot indicate the movement in the z-axis
8 Conclusion

The goal of this bachelor thesis was to find solutions for the optic of an optical flow sensor, to realize this solution, to build a working prototype and to test it. For the research a lot of time to find an optimal solution for this problem was invested. Generally, there are two possibilities: autofocus or telecentric lenses. It turned out that the solution with an autofocus working with liquid lenses is the most suitable for this project. It also became apparent that optical mouse sensors do not work with very fast velocities and, as seen in the experiments, there are also problems if the movement is too slow.

One problem was to attach the lens to the sensor to get useful and sharp images. For this, a fixed optic was used. The difficulties were the correct positioning of the lens and the readout of the image of the mouse sensor which is very important to make a declaration about the quality of the captured image.

Unfortunately, the evaluation of the solutions and the readout of the image took a lot of time and therefore the liquid lens was not implemented. This reduces the working range and the accuracy of the sensor. But for distances up to 110 mm, the sensor works pretty well on most surfaces. Errors are caused by too slow movement, noise and inaccuracy of the distance sensor and because the distance sensor and the mouse sensor does not point exactly at the same area for most distances.

The accuracy in general is bounded by some velocities and heights. This makes it difficult to use it on robots. Optimization is probably possible, for example with the implementation of the autofocus or more precise distance measurement. That slow movements are not recognized is an internal problem of the mouse sensor and cannot be influenced. That the sensor does not work on extremely plain and structureless surfaces is also a problem that cannot be solved. The implementation of the autofocus could improve the results slightly but due to the low resolution of the mouse sensor, it is almost impossible to find the focus for sharp images. Another option would be to increase the magnification (zoom) of the optic to register slower movements.

The experiments showed that the error is below 5 % if the velocity is larger than 1000 mm/s or if the distance is more than 120 mm. For distances below 95 mm the error is below 1 % on flat surface.

Nevertheless, it is shown that these kinds of sensors are indeed usable for specific tasks where the limits are well known. The prototype sensor is built with standard hardware and is therefore very universal useable. The output can directly be used without the need of special software. Compared to the former project, where hardware form “National Instruments” and LabVIEW Software was used, this project completely gets along with standard elements. Furthermore, this method is much cheaper than for example laser range data. If the sensor would be produced in large amounts, the costs are quite low and it could be implemented in simple and cheap robots.
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Figure 14: http://de.wikipedia.org/