Relative Motion in One Dimension

1. Objectives

- Observe and understand motion relative to a moving reference frame;
- Measure the relative position of a Motorized Cart moving at constant velocity with respect to the Time-of-Flight VL53L0X Motion Sensor connected at the Raspberry Pi;
- Use the PhyPiDAQ-Software to display the relative position versus time in real-time for the Motorized Cart moving along a straight line towards or away from the Motion Sensor that can also be in motion or standstill.
- Analyse the relative position versus time diagrams for the following types of relative motions in one dimension:
    - Motorized Cart and Motion Sensor move in opposite directions towards each other;
    - Motorized Cart and Motion Sensor move in opposite directions away from each other;
    - Motorized Cart and Motion Sensor move in the same direction;
- Compare and contrast the relative position versus time diagrams of the three relative motions to the position versus time diagram of the Motorized Cart with respect to the sensor at rest.
- Employ spreadsheets like LibreOffice or Excel to analyse the shape and slope of relative position-time and velocity-time graphs based on the measurements stored in .csv files.
- Calculate the relative velocity of the Motorized Cart with respect to the Motion Sensor set as reference frame moving in different directions;
- Determine the velocity of the moving sensor set as reference frame based on the slope of relative position-time graphs.
- Interpret the difference between the relative velocity and difference in velocities.

2. Materials and Equipment

Raspberry Pi 3B+ or 4B	Variable Speed Motorized Cart
PhyPiDAQ-Software for Data collection	Reflector of metal, white or light colour, for reflecting the Laser beam towards the sensor's receiver
VL53L0X Motion Sensor	Jumpers to connect the sensor to the Raspberry Pi
Breadboard	Clamps
Tripod Stand	Rod

3. Set-up

Connect the VL53L0X Motion Sensor to the Raspberry Pi according to the circuit shown in Figure 1. The students used the Fritzing open-source program to build this circuit.

Connect monitor, mouse and keyboard to the Raspberry Pi and secure the breadboard with the sensor, as shown in the Figure 2 or in the Figure 3. Or, you can use any other materials from your lab to fix the sensor into the right position to run the measurements.

Place the Variable Speed Motorized Cart about 3cm in front of the sensor. Position the reflector on the side facing the sensor, perpendicularly oriented to the Laser beam. According to the datasheet of the VL53L0X Motion Sensor, a light-coloured reflector provides a better quality of the measurements.

A Variable Speed Motorized Cart from the Phywe Company with three-stage switch for forward, off, and reverse motion is used in this experiment. The wheels are geared to operate at the constant speed, which is adjusted through the speed control slider. Therefor this Motorized Cart is used to experience uniform motions with constant speed. Alternatively, one can use other Motorized Cart from other company.

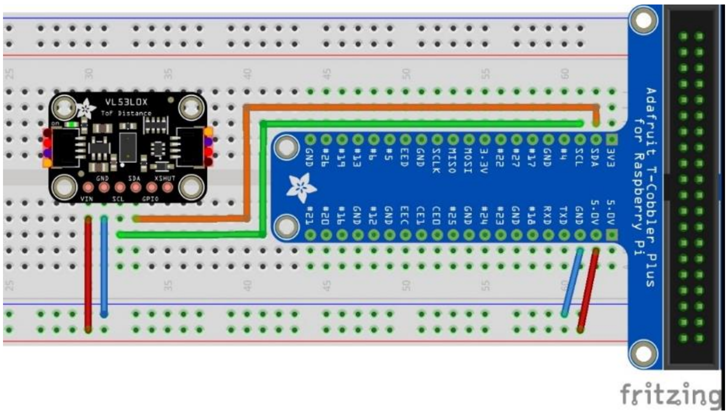

Figure 1 Connecting the VL53L0X Motion Sensor to the Raspberry Pi. The VL53L0X communicate to the Raspberry Pi via I^2C-Interface.

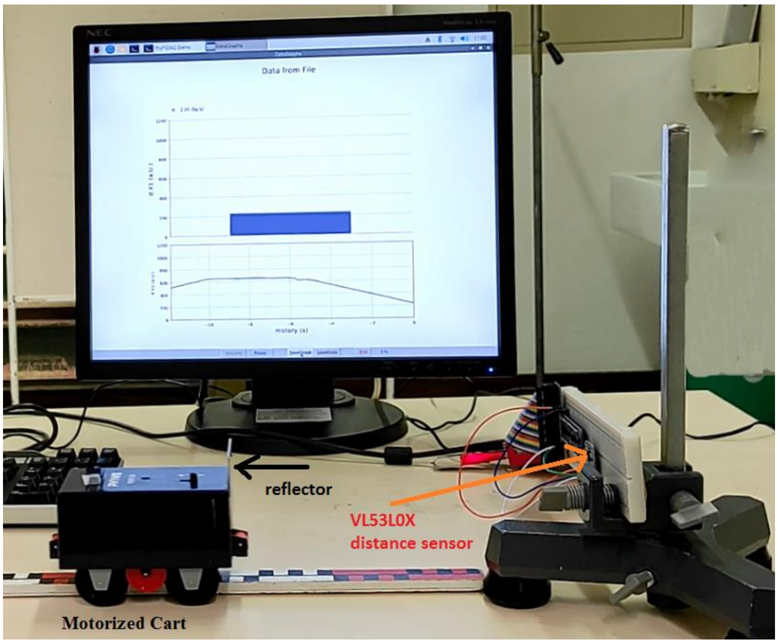

Figure 2 Set-up of the experiment with VL53L0X Motion Sensor and Variable Speed Motorized Cart

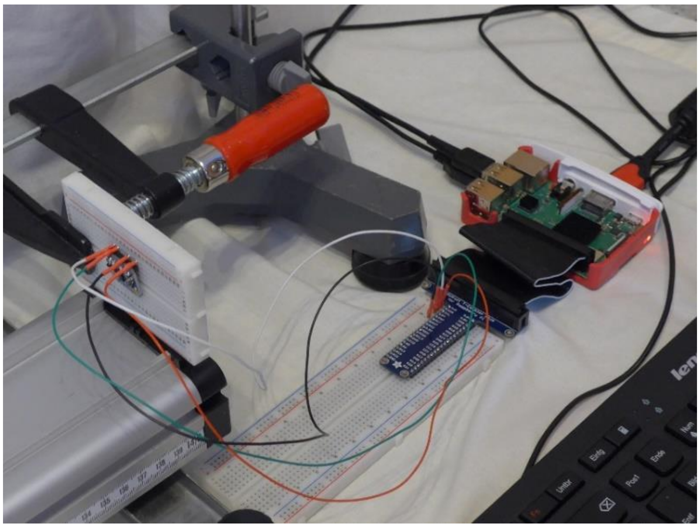

Figure 3 Connecting the VL53L0X Motion Sensor to the Raspberry Pi

4. Procedure

In order to visualise the Cart's position in real time one has to go through the following steps. Watch this video https://youtu.be/Vd5KpSkuN2w first to get an insight into the procedure of configuring the experiment.

On the Graphical Interface of the PhyPiDAQ Software open the Work directory where the configuration files are going to be saved. In the `DAQ config`: text box introduce the pre-configured file `Distance.daq` from the directory **/home/pi/git/PhyPiDAQ/examples**.

Alternatively, choose the `default.daq` file and edit this according to the VL53L0x_postion_vs_time.daq saved as .pdf file and uploaded in the **Activity-Based Physics** web page. To activate the VL53L0x Motion Sensor remove the #-Sign from the command DeviceFile: config/VL53LxConfig.yaml and press the `reload device config` button at the bottom of the `PhyPi Config` window. Click on the `Device Config` Button at the top of the window to change into the Sensor's configuration window. Once there one can edit the .yaml configuration of the VL53L0x Motion Sensor according to the VL53LxConfig.yaml saved as .pdf file and uploaded in the **Activity-Based Physics** web. Here one can choose between the two sensor types and enter the desired measuring range. Note to click on `EditMode` at the top of `PhyPi Config window` to change or modify the commands in the configuration files.

After all the stages are finished, one can start the measurement by pressing the `StartRun Button` on the main graphical interface of the PhyPiDAQ. The measurement window opens. This video shows the experimental run with the display of the relative position of the Motorized Cart in respect to the Motion Sensor set to move or to rest: https://youtu.be/hmwqKuE78n8

Observe the measured Position versus Time graph of the Variable Speed Motorized Cart set to move forwards, to stand still and to move backwards with respect to the stationary sensor. Compare the Position versus Time graph of the moving Motorized Cart while the Motion Sensor moves away from the Cart, or towards the Cart.

Save the Position vs. Time graph on the measurement window by pressing the `SaveGraph` Button on the taskbar. The picture called DataGraph.png is saved in the same folder containing. daq and .yaml configuration as well as the recorded measurements in the .csv file. Repeat the procedure for the relative motion of the Motorized Cart relative to the moving sensor.

Press the `End` Button to complete the measurements. To repeat the measurements, choose to don't exist the PhyPiDAQ in the coming out menu window. The same. daq configuration is meant to be used to run again the experiment, for instance by setting the Motorized Cart at a higher speed.

5. Data Collection

The PhyPiDAQ-Software enables measurements' collection in .csv files. In the Distance.daq configuration one has to activate `DataFile: testfile.csv` as well as `CSVseparator: ';'` by removing the #-Sign. `Testfile` can be renamed to the purpose of the experiment. Add the #-Sign to disable the `DataFile: null` command. On the Raspberry Pi's Terminal the name of the .csv file comes up.

Another option is to press the `SaveData` Button on the task bar of the measurement window, as shown in the Figure 4.

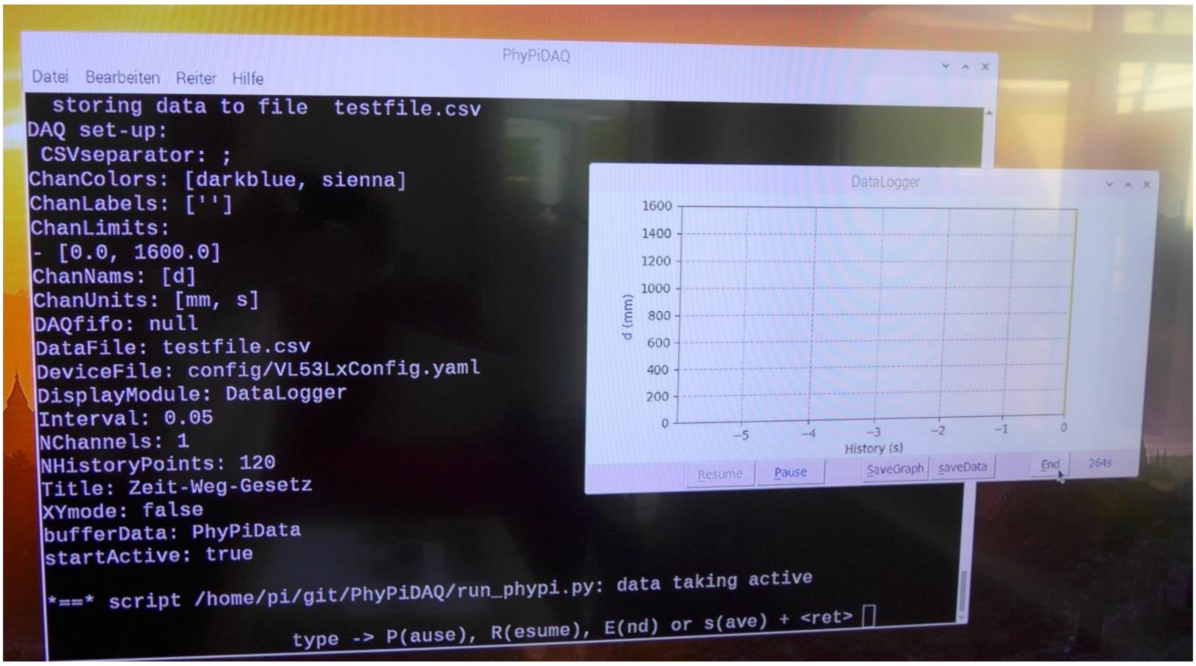

Figure 4. Raspberry Pi's Terminal and PhyPiDAQ measurement window. The recorded data are stored in .csv file. Alternatively, one can save data in .dat file by pressing the `SaveData` *Button on the task bar of the measurement window.*

6. Data Analysis

- Observe the Position vs. Time graph in real-time and compare it to the real motion of the Motorized Cart while the Motion Sensor, as a reference frame, is in motion or standstill state. Make predictions about the changes in the graph, if the Cart moves faster, slower, in the positive or negative direction. How does the graph change if the Motion Sensor moves in respect to the Cart set at rest? Now the Cart and the Sensor move at the same time. Anticipate the changes in the Position vs. Time graph if they move towards each other or away from each other.

- In the Figure 5. the position of the Motorized Cart is measured by two observers. The observer at rest is R. He stands at the left edge of the measuring-rod. The sensor S is the moving observer. A reference frame is attached to each observer. The position of the Cart measured by the observer R, X_{CR} , is related to the position of the Cart to the moving Sensor S, X_{CS} , as well as to the position of the Sensor S to the observer R, X_{SR}. What is the relationship between the relative velocity of the Cart with respect to the Sensor v_{CS} and the velocity of the Sensor v_{SR} ?

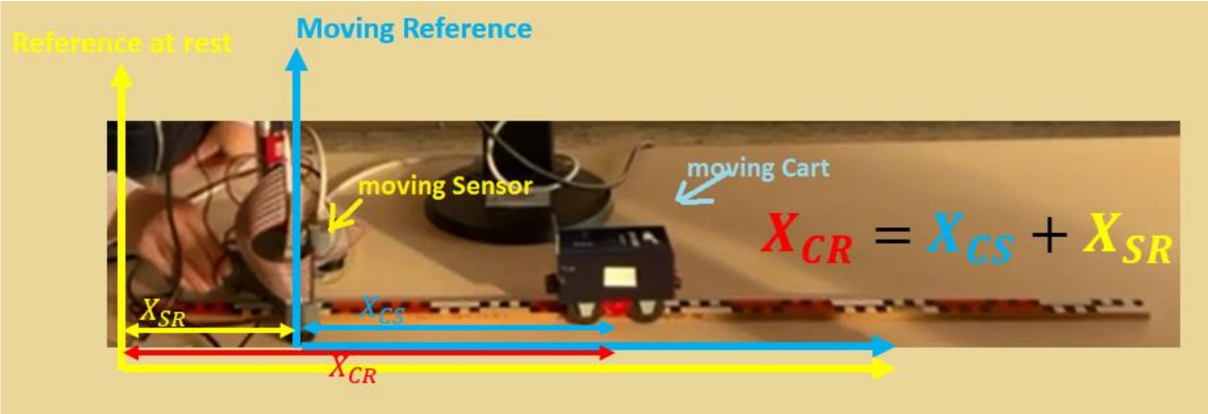

Figure 5. Position of the Motorized Cart measured in two reference frames.

The equation of relative velocity of the Cart with respect to the moving Sensor is:

$$\vec{v}_{CR} = \vec{v}_{CS} + \vec{v}_{SR}$$

Consider the velocity direction of the Sensor with respect to the observer R at rest as the positive direction. This is the reference direction to assign sign to the velocities.
Now consider Cart and Sensor moving in the same positive direction

- with equal velocities $v_{CR} = v_{SR}$;
- with unequal velocities $v_{CR} < v_{SR}$;
- with unequal velocities $v_{CR} > v_{SR}$;

-Sketch predictions for the corresponding position-time graph of the Cart and of the Sensor with respect to the observer R at rest. Label these predictions. When is the relative velocity of the Cart with respect to the Sensor positive, negative and zero?

-Answer the same questions when the Cart and the Sensor move in opposite direction.

-Run the experiment to measure the relative position vs. time of the Cart with respect to the Sensor. Set the slider of the Motorized Cart at a constant velocity. Observe the position vs. time graphs displayed in the PhyPiDAQ-measurement window and compare them to your predictions for the situations listed above.

Additionally, watch the video https://youtu.be/hmwqKuE78n8 to visualize the relative position of the Cart to the Sensor, when they move in the same or in opposite direction.

-The Figure 6. shows the position vs. time graph of the Cart in a multistep motion with respect to the Sensor at rest. The average velocity is defined as the rate of change of position with time. Calculate the average velocity of the Cart moving away from the motion Sensor, as well as moving towards the Motion Sensor.

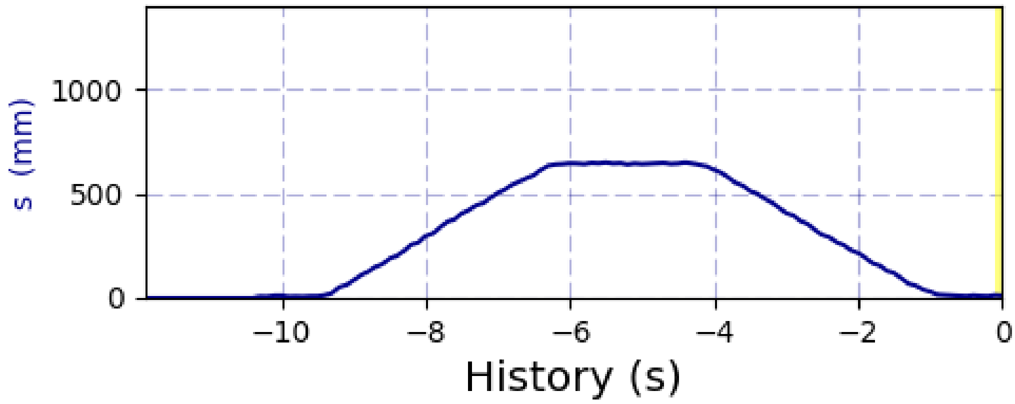

Figure 6. Position vs. time graph of the Cart moving away from, as well as moving towards the Motion Sensor set at rest.

- The relative position of the Cart with respect to the moving Sensor in the same direction is shown in the Figure 7. Which object is moving faster?

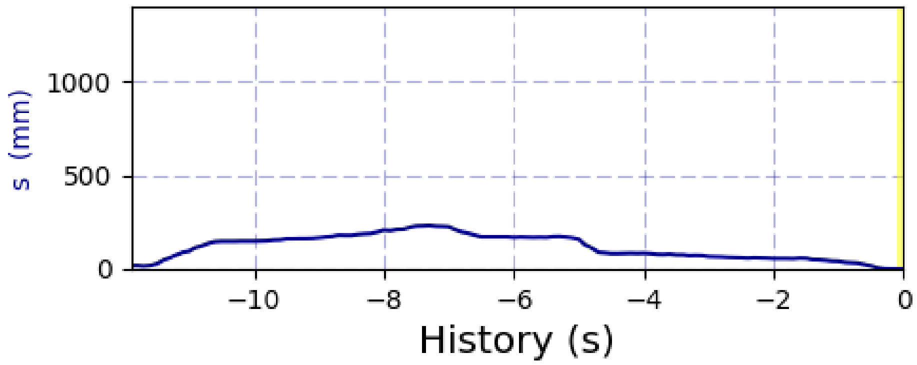

Figure 7. Relative position vs. time graph of the Cart moving with respect to the Sensor in the same direction.

- Explain why the relative position of the Cart with respect to the moving Sensor remains positive when the both objects move forwards and backwards. Explain how the Cart and sensor should move, so that the relative position becomes negative?

- Now open the relative_motion_opposite.csv file in Excel or in LibreOffice installed on the Raspberry Pi. A more accurate analysis of the recorded relative position of the Cart with respect to the sensor at different instants is possible. The relative position vs. time of the Cart and Sensor moving in opposite directions is shown in the Figure 8.

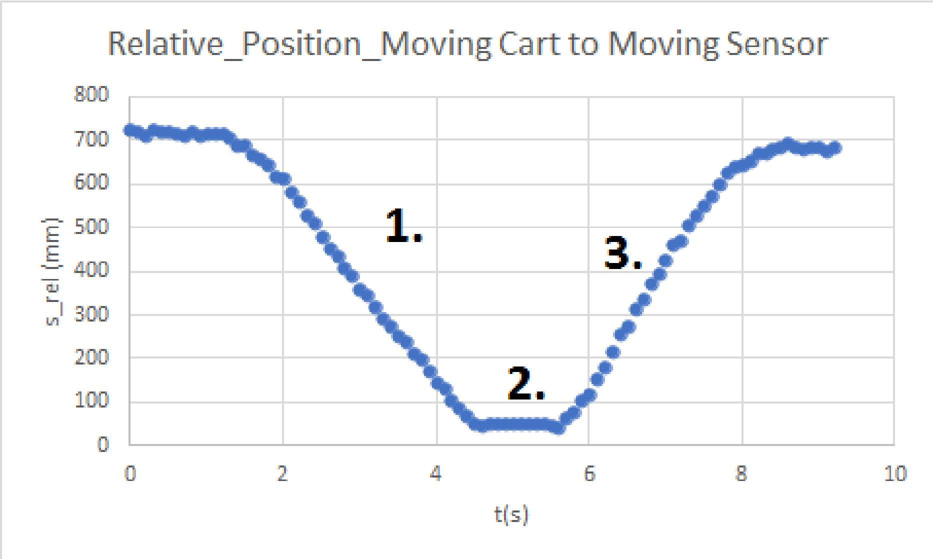

Figure 8. Relative position vs. time of the Cart to Sensor, both moving in opposite directions.

Consider the velocity direction of the Sensor with respect to the observer R at rest as the positive direction. This is the reference direction to assign sign to the velocities.

Given the equation of relative velocity of the Cart with respect to the moving Sensor $\vec{v}_{CR} = \vec{v}_{CS} + \vec{v}_{SR}$, what direction moves the Cart in each phase, when is known that:

- In the 1st phase the Sensor moves to the right;
- In the 2nd phase the Sensor is at rest;
- In the 3rd phase the Sensor moves to the left;

– The relative velocity of the Cart to the moving Sensor is the slope of the line on a position versus time graph, which one can get by selecting the Trendline in the scatter chart of the measured data. By breaking up the time into intervals one can determine the relative velocity v_{CS} of the Cart to the Sensor in the 1st and 3rd phase, as shown in the Figure 9. Describe a method to determine the velocity of the Sensor, when the Cart's velocity to the observer at rest is known.

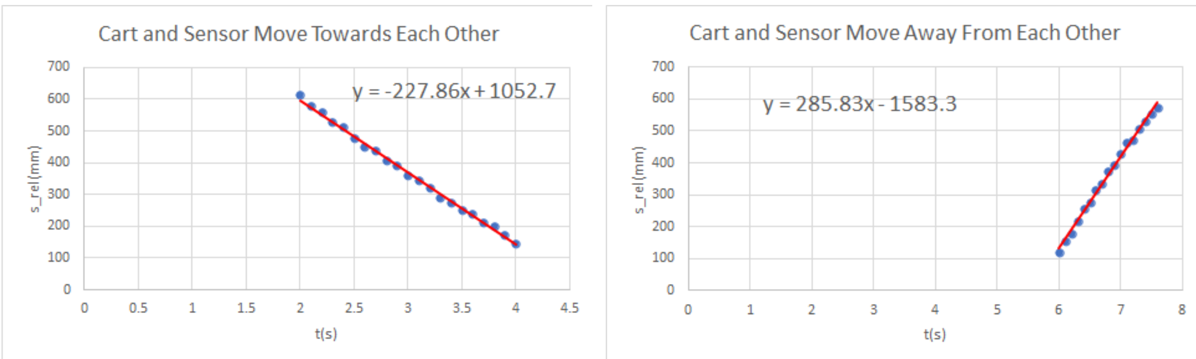

Figure 9. *Best Fit Line and Formula for the Cart's relative motion to the moving Sensor in opposite direction.*

- The average velocity of the Cart to the Sensor at rest $\mathrm{v_{CR}}$ has been calculated according to the graph in the Figure 6. A more accurate value of $\mathrm{v_{CR}} = 209{,}8\ mm/s$, one can obtain from the motion_cart_senor.csv file as the slope of the best fit line for the Cart moving away from the Sensor at rest, in the interval from 1.4s to 3.4s. Based on the constant value $\mathrm{v_{CR}} = 209{,}8\ mm/s$, make use of the relative velocity of the Cart to Sensor $\mathrm{v_{CR}}$ in the Figure 9. to calculate the average velocity of the Sensor to the observer R at rest $\mathrm{v_{SR}}$ in the 1st and 3rd phase of the multistep motion.

7. Experiment

- Repeat the measurements a few times on your own. Change the Cart's velocity by moving the slider. Go through the same questions for different Sensor's velocity.