Characterisation and development of a novel low-cost radar velocity and depth sensor

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Highlights

- A low-cost (<40AUD) sensor for depth and velocity measurement is described and characterised.
- The low cost and power usage allow for wide-scale deployment with low maintenance.
- Novel features include a 3D printed radar lens for added sensitivity and an accelerometer for self-measurement of the installation orientation.

Introduction

The challenges of urbanisation and climate change increase the need for stormwater monitoring to facilitate the assessment and improvement of the health of urban waterways. Water depth and flow rate are key quantities used to assess the impact of urban stormwater on the ecosystem of receiving waterways. The high spatial and temporal variability of these waterways calls for higher spatial and temporal measurement resolutions (Kerkez, et al. 2016; Shi, et al. 2019). A major issue with current measurement solutions such as the QCam (Fulton, et al. 2020a) or HACH AV sensor (HACH 2021) is their cost of several thousand dollars and difficulty to install and maintain (Ahmed, et al. 2020). This makes wide scale deployment infeasible on limited budgets. New low-cost sensing technologies promise to make feasible high-resolution monitoring schemes. Thus, development of a low-cost velocity and depth sensor is of interest for urban water management schemes.

Significant progress has been made in the space of low-cost radar-based water sensors: radar-based measurement techniques for both velocity and depth measurements have been demonstrated by Ma (2020), and doppler radar has been implemented into an Arduino compatible sensor by Alimenti, et al. (2020) and have achieved river surface velocity measurement. A proposed low noise amplifier chip is tested in a radar velocity sensor by Lin, et al (2020) who demonstrates performance in a field test. Presentation of a radar sensor design which is both field-ready and low-cost has not yet been done and is the focus of this work. The combination of water depth and velocity measurement of the presented sensor allows for the volumetric flow rate to be calculated from the sensor data via the velocity-area method.

Methods

Sensor Design

The sensor design consists of an XM132 radar module, a KXTJ3-1057 accelerometer, and an ATmega328PB microcontroller (MCU) integrated onto a single PCB. The microcontroller manages the power states, shutting off components when not needed. The XM132 is a small off-the-shelf module which generates, transmits, and receives the 60 GHz radar. The reflected radar signal from the water surface is used to extract the velocity and distance of the water surface. The accelerometer is used to determine the installation orientation of the sensor which is needed in extracting distance and velocity. This means the orientation does not need to be measured manually during installation. The sensor is enclosed in a 3D printed housing displayed in Figure 1. 3D printing is used to form a lens on the front of the sensor to focus and collect the radar signal, increasing sensitivity by 70%. The sensor interfaces to a datalogger via UART and requires a 3.3V supply voltage. The hardware and firmware design files needed for the reader to construct the sensor are made available under an open hardware licence.

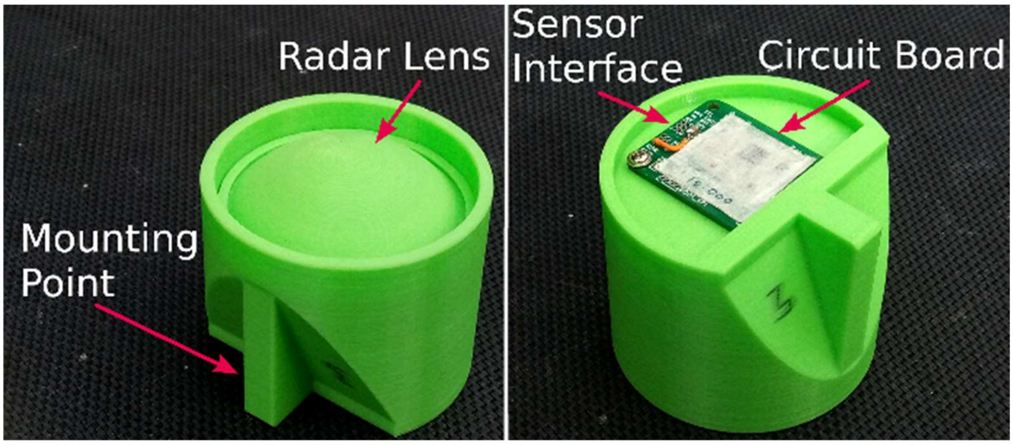

Figure 1. Left: front of radar sensor enclosure displaying radar lens and mounting point. Right: back of radar sensor with back cover removed. This displays the circuit board and sensor interfaces to which a cable can be soldered to connect the sensor to a datalogger. The sensor measures 60 mm in diameter and 50 mm in height.

Data Processing

The raw radar data provides time series measurements of reflected signal strength over a range of distance bins. The line of sight distance, D, to the water surface can be determined by the distance bin with the greatest reflected signal strength. To convert this to a water depth, for a sensor suspended a height H about the channel bed and at an angle θ from the vertical, trigonometry gives:

$$d = H - D\cos\theta.$$

Where d is the water depth. The reflection of the radar signal off small surface waves introduces an average doppler frequency shift, Δf, proportional to their velocity. Evaluating the Fourier transform on the time series measurements allows Δf to be determined and thus the surface velocity, v, via:

$$v = \frac{c\,\Delta f}{2f\ \sin\theta}.$$

Where c is the speed of light and f = 60 GHz the frequency of the radar system (Plant, et al. 2005). This Fourier transform is evaluated on the MCU via digital signal processing. This gives an intensity spectrum of the presence of different frequency components in the signal with the frequency of highest intensity taken to be Δf. Determination of the doppler frequency shift is non-trivial as significant noise is present in the signal. To combat this multiple radar scan readings are taken per measurement and the calculated doppler frequency shift from all readings are averaged into a final datapoint.

Lab Characterisation

The radar sensor was characterised in a lab flume. Three of the sensors were suspended 740 mm above the flume bed pointing towards the flow at an angle of 15 degrees from the horizontal. The sensors were labelled A, B, and C with B positioned along the centreline, A and C positioned to either side 80 mm from the centreline. For each measurement the flow velocity was recorded via the average of two venturi meters positioned just below the water surface, the flow depth was recorded via the average of two rulers printed on the side of the flume. The two sets of meters were positioned on either side of the water surface region measured by the radar and give an indication of the average flow conditions in this region. The raw radar data was processed off-sensor on a computer with 12 readings taken per datapoint. The flow depth was able to be swept between 15 to 125 mm and the flow velocity from 0.1 to 1.2 m/s. A diagram of the experimental setup is shown in figure 2.

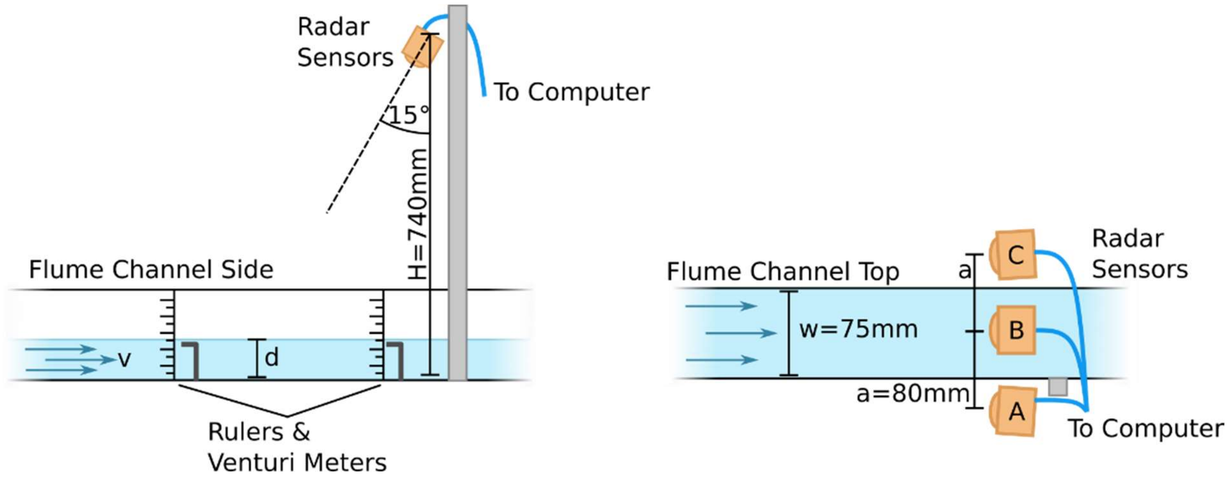

Figure 2. Diagrams for lab setup for characterisation of radar sensor. Left: side view, right: top view. Flume pump and flow control valves not shown.

Results and Discussion

The velocity test data from the lab characterisation is shown in Figure 3 and the depth test data in Figure 4. For the velocity test it is seen that the measurements from sensor A and B have a high linear correlation with R^2 greater than 0.88 and their gradient differs from 1 by less than 6%. Sensor C however performs more poorly on these metrics. It is seen that the sensors are challenged at velocities less than 0.3 m/s with a near-flat response to velocity in this range. It is noted that low velocities are generally a challenge for the radar-based sensors (Fulton, et al. 2020b). For the depth test, sensors A and B display very good linear relationships with gradients of the line of best fit differing by about 2% from 1 with depth offsets of less than 10 mm, and R^2 values of greater than 0.95. The linear response of the sensors is seen to not deviate from a linear relationship even at low depths. Again, sensor C performs more poorly than sensors A and B. For all linear regressions the probability of the null hypothesis that the gradient is zero is $p < 0.0001$, thus they are statistically significant to a high degree of confidence. These tests indicate that the sensor fairly capable of measuring the water velocity and depth. Future work being undertaken is directed towards in-field and long-term testing of the sensors.

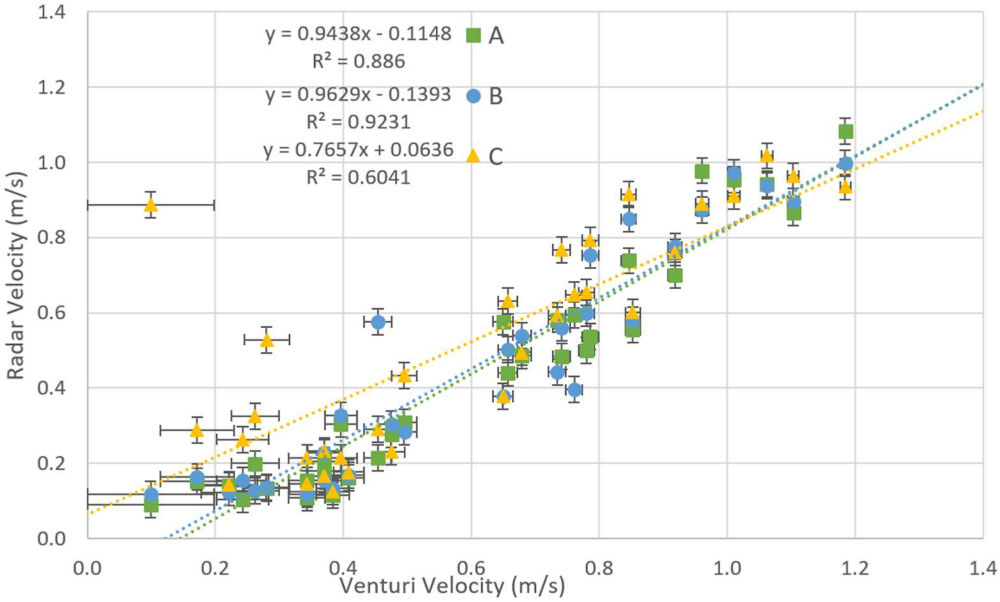

Figure 3. Velocity data from the lab characterisation. The plot displays the correlation between the sensor's measured velocity and venturi meter velocity. The measurements from each of the sensors A, B, and C are displayed in their own data series with their own line of best fit. The equation for the line of best fit and its R^2 coefficient are displayed next to the plot legend.

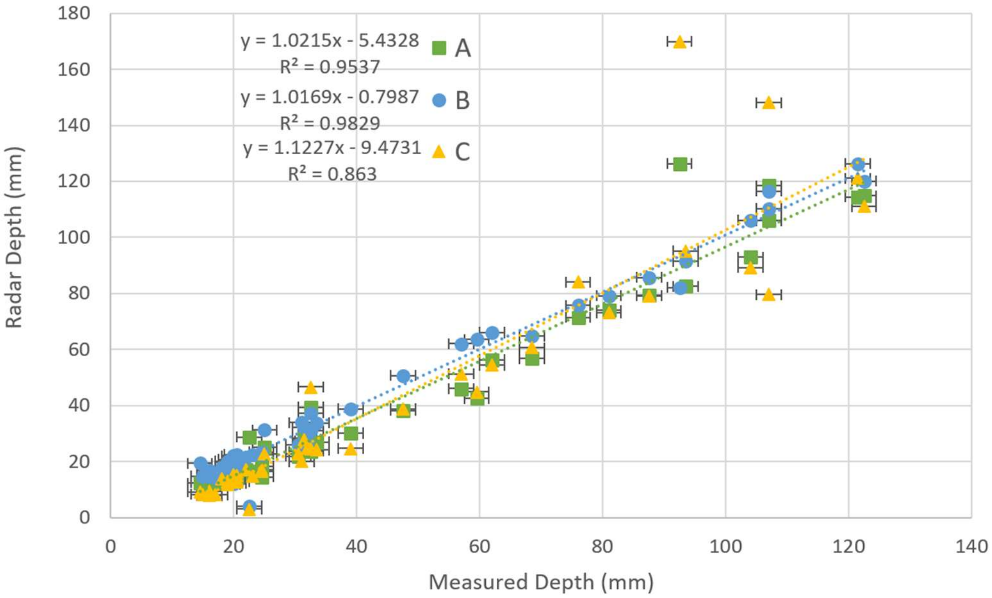

Figure 4. Depth data from the lab characterisation. The plot displays the correlation between the sensor's depth and the measured depth. The measurements from each of the sensors A, B, and C are displayed in their own data series with their own line of best fit. The equation for the line of best fit and its R^2 coefficient are displayed next to the plot legend.

Conclusions

A novel low-cost water velocity and depth sensor based on radar measurement was developed and characterised. The lab characterisation indicated that the sensor was able to successfully measure the water velocity and depth with linearity errors in the gradient of less than 6% and 4% respectively. The use of 3D printing allowed for a radar lens to be fabricated into the enclosure, significantly boosting the sensitivity of the sensor. The sensor's low cost (<40 AUD), power consumption and maintenance allow it to enable high-resolution water quality monitoring schemes.

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