MATEC Web of Conferences **13**, 01002 (2014)
DOI: 10.1051/matecconf/20141301002

Towards an Improved Flow Rate Estimation Method

Muhammad Hazim bin Suffian [1] and Mark Ovinis [1,a]

[1]Mechanical Engineering Department, Universiti Teknologi PETRONAS, 31750 Tronoh, Malaysia

Abstract. This paper presents the development of a technique for estimating flow rate. The intended application is to estimate the volume of oil spilled from a ruptured subsea pipeline, with improved accuracy over existing methods. In this work, two novel methods to estimate flow rate with high accuracy were considered. The first involves the use of 3D cameras to estimate volumetric flow rate and the other uses a 2D camera to estimate the flow velocity. Related works including 3D reconstruction, optical flow and the experimental setup are described. The 2D camera approach produced good results, with an error of 2% - 9%. On the other hand, the use of 3D cameras needs further work, as the cameras are unable to detect the flow. Future work for this approach will be focused on overcoming this limitation and developing the method further.

1 Introduction

The Deepwater Oil Disaster that occurred on 22nd April 2010 is the largest accidental spill [1]. It took the operator, BP and the US government 87 days to seal the oil well. Numerous efforts had been taken ranging from a specially built dome to junks and mud to control the leak. However, one issue still remained uncertain, which was the estimated volume of oil spilled into the ocean, as penalties imposed are based on the amount oil leaked. The most accurate method to date is a standard deviation of 2.6% by Crone [2]. As oil spills are typically in millions of barrels, an inaccurate estimate will result in a substantial error. Thus, there is a need to accurately estimate the total amount of oil leaked. In this work, a more accurate flow estimation technique is described. The development of this new method will enable the volume of oil spilled from a ruptured subsea pipeline to be estimated with higher accuracy. It may also have the potential to be applied to other flow rate estimation. Two types of technique were used to estimate the volume of oil spilled in the Deepwater Oil Disaster, those based on satellite imagery and those based on video of the flow [3]. The estimated flow rate varies quite significantly for each method. Table 1 summarizes the different flow rate estimation techniques, the estimated flow rates and their limitations. Estimates based on video of the flow are generally more accurate than estimates based on satellite imagery.

Article available at http://www.matec-conferences.org or http://dx.doi.org/10.1051/matecconf/20141301002

Table 1. Flow rate estimation methods and their limitations

Method	Author	Estimated Flow Rate (bbls/day)	Limitation
Satellite imagery without Bonn Convention Protocol	John Amos [4]	5,000 – 20,000	Assumption of no oil burned and evaporated
Satellite imagery with Bonn Convention Protocol	Ian Mcdonald [5]	26,500	Bonn Convention not recommended for analysing large spills [4]
Optical Plume Velocimetry	Timothy Crone [2]	50,000 – 100,000	Poor imaging system • Low speed (fps) • Low resolution
Angle of flow and the rate of flow	Eugene Chiang	20,000 – 100,000	Assumption on the percentage of oil from the flow. No information inside the flow.
Particle Image Velocimetry	Steven Wereley [7]	72,129 (±20%)	

1.1 Flow Rate Estimation

Flow rate is defined as the volume of fluid that flows past a given cross sectional area per second. There are two general methods to estimate flow rate, volume based and velocity based. One way to estimate flow rate is to determine the rate of volume change over time. The volume of fluid can be estimated based on a 3D reconstruction of a flow [10]. The flow rate can be estimated per Equation 1:

$$Q = dV/dt \tag{1}$$

where Q is the flow rate [cm3/s], V is the volume [cm^3] and t is the time [s]. For a steady and incompressible fluid flow involving only one stream of a specific fluid flowing through a control volume [6], the flow rate is given by Equation 2:

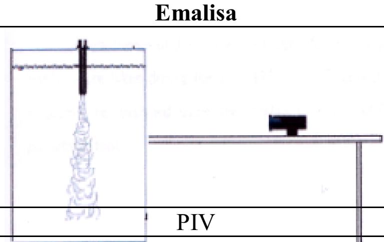
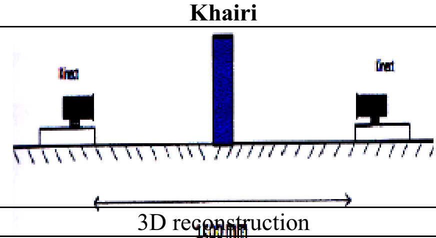
$$Q = vA \tag{2}$$

where v is the velocity [cm^2] and A is the cross sectional area [cm^2].

1.2 Related Works

Methods based on video of the flow are more accurate compared to those based on satellite imagery, as evident by the results obtained from work of Crone, Chiang and Wereley. Recent work on video analysis to estimate flow rate include that by Emalisa [8] and Khairi [9], who did some preliminary work on flow rate estimation. Khairi used a Kinect for 3D reconstruction, with the aim of eventually using this technique for flow rate estimation. Kinect is an optical camera equipped with a depth sensor, and is able to return 3D coordinates of an object. An image processor uses an infrared pattern [11] to calculate the object depth. Table 2 shows a summary of their work.

Table 2. Emalisa and Khairi's flow estimation method

Author	Emalisa	Khairi
Experimental Setup		
Approach	PIV	3D reconstruction
Percentage Error (%)	4.26	7-12
Limitations	Flow is assumed constant	Use of solid objects

2 Methodology

2.1 Experimental Setup

Crone's experimental setup (which was used to simulate an oil spill from a pipeline), as shown in Figure 1, was replicated. In this work, three Kinects place 120^o apart were used in place of the single 2D video camera, to facilitate 3D reconstruction of the flow.

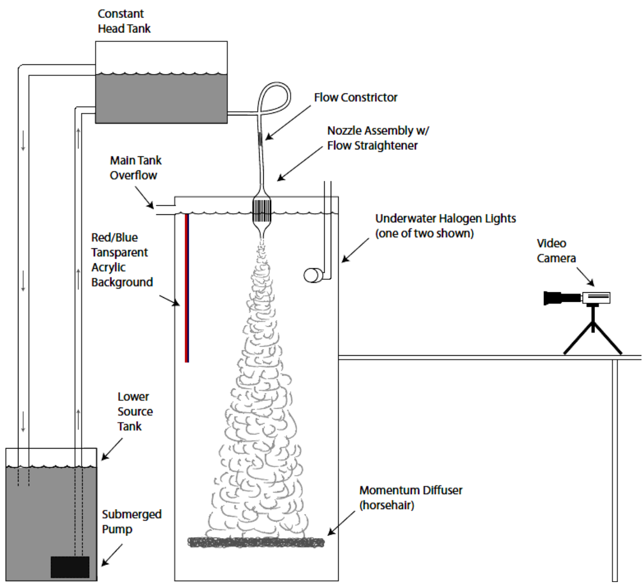


Figure 1. Crone's experimental setup [2]

2.2 Volume Estimation

For volume estimation of a flow, 3D reconstruction based on point clouds from three Kinects was performed. A transformation matrix and Iterative Closest Point that relates the point cloud of one Kinect to another were used. The volume of a basic alpha shape [7] for the combined point cloud is the volume of the flow. Alpha shapes are a generalization of the convex hull of a point set, essentially the volume bounded by a set of points.

2.3 Optical Flow

An alternative technique based on optical flow was also implemented to estimate the velocity of the fluid flow. Optical flow is the apparent motion of brightness patterns in an image corresponding to the motion field [12]. One of the most common optical flow methods is that by Lucas and Kanade [13]. The algorithm attempts to find an optimal value for a disparity vector, *h*, which represents an object's displacement (pixel/frame) between successive images [14]. Their method presents a desirable level of flow accuracy which is capable of distinguishing regions varying in activity level [14]. The velocity of a fluid flow can then be estimated as given in Equation 3:

$$v = h.FPS.k \tag{3}$$

where v is velocity [cm/s], h is pixel displacement [pixel/frame], FPS is the camera speed [frame/s] and k is calibration constant (cm/pixel). The assumptions made in estimating velocity were that the flow was assumed to be in a pipe (conservation of mass) with a circular cross section with a region of interest near the nozzle chosen.

3 Results and discussion

Videos of flow from the experimental setup as shown in Figure 1 had been successfully captured. Figure 2 shows a sample video frame with an average camera speed, FPS = 19 frame/s and with a calibration constant, k = 0.1319 cm/pixel.

Figure 2. Video of flow

Unfortunately, the flow cannot be detected by the infrared laser patterns from the Kinect. As such, depth values and hence 3D reconstruction of the flow could not be obtained. To further develop this method, a solid object was used in place of the flow. The 3D reconstruction of the solid object, by merging information obtained from three Kinects, is shown in Figure 3.

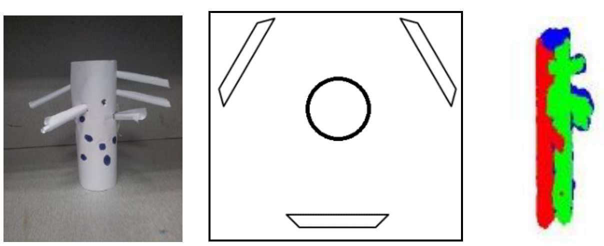


Figure 3. (a) Solid object used (b) Arrangement of the three Kinects (c) 3D reconstruction

The volume of the reconstructed 3D object, as shown in Figure 3, was estimated with alpha shapes. The estimated volume was 1018.4 cm^3 while the actual volume was estimated to be 640.96 cm^3, an error of 58.89%. The error is mainly because estimating volume for a point cloud is inaccurate. The estimated flow rate based on optical flow, as shown in Table 2, yielded better results.

Table 2. Flow rate estimation based on optical flow

Parameters	Flow 1	Flow 2
Pixel displacement, h [pixel/frame]	2.0677	2.1276
Velocity, v [cm/s]	5.1819	5.3320
Diameter [cm]	2.9	2.5
Area, A [cm^2]	6.6061	4.9094
Estimated flow rate [cm^3/s]	34.2321	26.1769
Actual flow rate [cm^3/s]	33.5189	24.0132
Percentage Error [%]	2.08	9.01

The error for flow 2 is higher. The probable cause of the higher error is because of the presence of bubbles in the flow, which reduced the accuracy of the estimation. As such, the technique may not be appropriate for flow where the amount of bubbles is significant.

4 Conclusions

Two approaches were considered to estimate flow rate better. The 3D approach needs further work as Kinect is unable to detect depth underwater as originally thought. Future work for this approach can be focused on overcoming this limitation and on developing more accurate techniques on volume estimation from a point cloud. A possible solution would be the use of a 3D camera based on optical images rather than infrared patterns. The optical flow approach produced a low error of 2% - 9%. Future work should focus on improving the technique so that it is robust in the presence of bubbles in the flow. As a conclusion, a more accurate method in flow rate estimation was developed.

References

1. Moss, Laura. "The 13 Largest Oil Spills in History." Mothernature Network. N.p., (16 July 2010). “http://www.mnn.com/earth-matters/wilderness-resources/stories/the-13-largest-oil-spills-in-history>”.
2. Crone, T. J., McDuff, R. E., & Wilcock, W. S., Experiments in fluids. **45(5)**, (2008) 899-915.
3. Prepared by CRS; estimates and timeline from National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, The Amount and Fate of Oil, Staff Working Paper, (October 6, 2010). “http://www.oilspillcommission.gov”
4. John. "Gulf Oil Spill Rate Must Be Much Higher Than Stated - 6 Million Gallons So Far?" Web log post. Skytruth. N.p., 27 Apr. 2010. “http://blog.skytruth.org/2010/04/gulf-oil-spill-rate-must-be-much-higher.html”
5. Gillis, Justin. "Size of Oil Spill Underestimated, Scientists Say." The New York Times. N.p., 13 May 2010. “http://www.nytimes.com/2010/05/14/us/14oil.html?_r=1&”
6. Munson, Bruce Roy. *Fundamentals of Fluid Mechanics*, Sixth Edition. 6th ed. Hoboken, NJ: Wiley, 195 (2009)
7. Edelsbrunner, H., & Mücke, E. P., ACM Transactions on Graphics (TOG), **13(1)**, 43-72 (1994)
8. Kamsani,E. *Development of an automated flow rate estimation method.* Dissertation, Universiti Teknologi PETRONAS, Malaysia. (2012)
9. Rahim,K. *Development of a 3D automated flow estimation technique.* Dissertation, Universiti Teknologi PETRONAS, Malaysia. (2012)
10. Stelldinger, P., & Latecki, L. J., In Proc. IEEE Int’l Conf. Image Analysis, (2006)
11. Andersen, M., Jensen, T., Lisouski, P., Mortensen, A., Hansen, M., Gregersen, T., & Ahrendt, P., Technical report ECETR-6, Department of Engineering, Aarhus University Denmark. (2012)
12. Robyn Owens, Optical flow. “http://homepages.inf.ed.ac.uk/rbf/CVonline/LOCAL_COPIES/OWENS/LECT12/node4.html”
13. Lucas, B. D., & Kanade, T., In IJCA, **81**, 674-679 (1981)
14. Bruhn, A., Weickert, J., & Schnörr, C., Lucas/Kanade meets Horn/Schunck: International Journal of Computer Vision, **61(3)**, 211-231 (2005)