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Tracking non-spherical particle position and orientation

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Abstract

A new method for tracking both position and orientation of non-spherical particles under free-fall conditions in water has been developed. The particles are recorded with background illumination in a water tank. Two cameras with 90° between camera axes allow for stereoscopic reconstruction. The implementation is done in Python using the toolbox OpenCV (Open Computer Vision). Contours around each particle image are determined. The contours are compared to back-projected contours from a three-dimensional model of the particle that is rotated to different orientations to find the best match. The method is tested on three cuboid shapes: a cube, a short rod with a square cross section and a rectangular flat cuboid. The latter falls with periodic oscillations while the two first show more advanced dynamics. Reynolds number based on terminal velocity of the particle is in the order of 250. It is also shown that a particle falling in the wake of another particle can get a significant change in terminal velocity and rotational dynamics.



(a) Sketch of setup with the used coordinate system



(b) Two views of a cube, long lines are epilines, contours around the particles are generated from the matched orientation.

Figure 1: The experimental setup with an example of processed images.

1 Introduction

Granulated plastics of different materials can be sorted by material types in a sedimentation process. The company Trebo has demonstrated an efficient implementation of this process, but to develop the process further, more detailed information about particle drag of the granulates are needed. Particle movement in dense flows are difficult to measure and to simulate. In simulations with Computational Fluid Dynamics coupled with Discrete Element Methods (CFD-DEM), the interaction between particle and fluid are modelled using drag coefficients. Models for non-spherical particle drag should include orientation, but this is not implemented in general Ma et al. (2022). This is partly because of lack of accurate data on such drag coefficients. Drag coefficients for non-spherical particles differ significantly from those of spheres as discussed with examples of correlations in Michaelides et al. (2023). A review by Mandø and Rosendahl (2010) discusses this in further detail.

Measurements of drag are often done with free-fall experiments recorded with a single camera, e.g. as done by Bagheri and Bonadonna (2016) and Goral et al. (2023). This method neglects effects of out-ofplane motion and cannot describe particle orientation in detail. One the few studies that use stereo vision to add both three dimensional path and particle orientation is Carranza and Zhang (2017). This study looks at axisymmetric shapes where the particle orientation can be described by two angles. The current work also uses stereo vision to measure free-falling non-spherical particles by tracking both particle position and orientation described with three angles. This is done for single particles and for particles in the wakes of other particles. The purpose is to provide data on particle dynamics and related terminal velocities. Data will be used to investigate how models based on drag coefficients work for regular particle shapes.

2 Experimental method

The experiments are carried out in a water tank with transparent walls (windows) and inner dimensions width \times depth \times height = 0.2 m \times 0.2 m \times 0.8 m, see figure 1(a). The liquid is tap water at 20°C with a very small amount of added dish washer rinse to minimize formation of bubbles when particles are immersed into the water. Measurement showed negligible change of water density and viscosity due to this additive. Two cameras (Basler acA1300-200um) are mounted with camera axes perpendicular to two of the windows and with an angle of 90° between the camera axes. The cameras are equipped with lenses with focal length of 16 mm and F-number of 11. This ensures reasonable focal depth in the tank volume visible for the both cameras. The two windows opposing the cameras are each illuminated with strong LED light source equipped with a "softbox" to create a uniform background illumination. The resolved area in the tank is roughly a box with height of 100 mm and with both depth and width of 125 mm. The box has equal distances to all vertical windows and is therefore not including tracks close to the wall. The top of the box is approximately 500 mm below the release point for the particles. This allows the particles to accelerate to terminal velocity before reaching the measurement volume.

Regular particles of three different cuboid shapes are used, see figure 2. The particles are machined out of black polystyrene plate (density 1030 kg/m³) with an accuracy of ± 0.05 mm. The particles have almost the same volume (the rod has 2% larger volume than the cube). The combined force due to gravity and buoyancy is therefore also almost the same for the three different particle types. The particles are released just below the water surface using a pair of tweezers. The resulting free-fall velocity in water gives Reynolds numbers based on terminal velocity and particle height in the order of Re ~ 250.

The present study also investigates how Open Source software can be used for complex tracking of particles. The data processing is done in Python using the toolbox OpenCV (Open Computer Vision), Bradski (2000), version 4.6.0. The mapping functions for the cameras are established from images of a checkerboard calibration target using a traditional Pinhole camera model including correction of radial distortion. The model does not directly include the change of refractive index at the interface between air and water. This is instead handled in the current case by the radial distortion correction in the camera model. The precision of the radial distortion correction has been checked by traversing a calibration target in the water tank and checking the accuracy of the back projection. Images of falling particles are identified from contours drawn around each particle. The contour is found with the Canny edge detection algorithm implemented in OpenCV.

The position of the particles are found with a traditional particle tracking algorithm, where epilines from each camera are used to find particle position in three dimensions based on a center point found from the detected contour. The orientation of a particle is described by three Euler angle representing successive



Figure 2: Dimensions for the three particle shapes investigated. The red vector indicates the main axis of rotation for two of the shapes.

rotation along the *x*-axis, the *y*-axis and the *z*-axis in the local coordinate system following the particle. These angles are converted into a rotation matrix. This can be multiplied with coordinates of particle points to the point coordinates after rotation. An algorithm is developed for calculating the projected image of a 3D model of the specific particle shape. The toolbox Alpha Shape finds a bounding polygon around the projected points from the particle corners and in some cases edges. This projection is a new contour that can be compared to the contour found on the particle image. It is now an optimization problem to find the orientation (three Euler angles) and exact position that give the best match between projected contours and detected contours on both cameras, simultaneously. Since gradient based optimization sometimes only find a local minima in deviation between detected and projected contours, the full solution space of Euler angles is first tested with a limited list of possible angles for a coarse global optimization. A gradient based optimization is then used on the best match. An example of matched contours is seen in figure 1(b).

The algorithm does not always find an accurate match. This can be due to e.g. tiny air bubbles on the windows or due to an orientation where a surface is almost parallel to both camera axes making the fit less sensitive to rotation along the axis perpendicular to the two camera axes. In this case the algorithm continues to investigate other positions on the track. When a good match is found, this is used as a starting guess for the neighboring points on the track. The use of a good starting guess means that the processing time for following points on the track is much smaller.

3 Results

In the order of 100 particle drops have been recorded for each of the three geometries. The recordings are done with a frame rate of 100 Hz and an exposure time of 2 ms. The particles move about a tenth of the particle height between two frames. Each recording results in a particle track that for each time step give the three coordinates x, y, z describing the position of the particle center and the three Euler angles describing the orientation. Examples of representative tracks for each geometry are visualized in three dimensions in figure 3

As seen in figure 3(a), the flat rectangular cuboid has motion with periodic oscillation along a horizontal axis. This axis is aligned with the longest edges of the cuboid and is marked as "the main axis of rotation" in figure 2. To quantify the oscillating behavior, a position on the track with a neutral orientation (largest surface oriented horizontally) as reference. For the other points on the track, a rotation matrix has been found to describe the rotation from the neutral orientation to the current orientation. The rotation matrix is converted into a rotation vector denoted Ω . This rotation is done along an axis through the particle center and parallel to this vector. The length of the vector is the angle of rotation. For the rectangular cuboid, Ω is well aligned with the axis marked in figure 2. The angle (length of Ω) is therefore a good approximation of the particle rotation axis indicated with a red vector in figure 2. This angle is shown as a function of time in figure 4

The vertical component of the particle velocity also shown in figure 4 has been found from simple differences between positions which result in the high frequency noise in the velocity. Note the change of sign to get positive values for the velocity. The noise can easily be filtered from the well-resolved tracks, but we have decided to present the raw data to illustrate the accuracy of the individual position estimates on the track. The velocity shows weak oscillations with peaks in velocity when the angle is close to zero. The mean velocity is 36 mm/s. The pattern of periodic oscillations is similar to the behavior of a flat disc, see Mandø and Rosendahl (2010). The regular periodic oscillations are observed in most tracks with the



Figure 3: Examples of three-dimensional tracks of the three geometries investigated.

rectangular cuboid in the present study, but it has also been observed that small disturbances, e.g. from a previous particle drop, can disturb the regularity of the oscillations significantly.

An example of the motion of a short rod with square cross section is seen in figure 3(b). This geometry also has the main changes in orientation along a horizontal axis aligned with the long edges of the particle, i.e. the axis shown in figure 2. The angle of rotation has again been estimated using the rotation vector from a reference position and this is shown in figure 5. The variation in angle is much less regular than for the rectangular cuboid and has a somewhat chaotic behavior. The shown track has been selected to represent a typically observed behavior. The particle starts almost in neutral orientation (upper long side oriented horizontally). It rotates between 60° and -60° . However, when a rotation to about -60° is reached, some smaller oscillations around this angle is seen. The vertical velocity component has much stronger and less regular oscillations that seen for the rectangular cuboid. The mean velocity is about 45 mm/s, which is significantly higher than for the rectangular cuboid. A considerably longer track is needed to get a representative value for the velocity and dynamical behaviour of the particle.

The cube has an even more complicated motion with rotation of orientation along all axes as illustrated in figure 3(c). This is difficult to quantify in a way that is easy to interpret. One way is to plot all components of the rotation vector Ω . This is shown for a track in figure 6. The shown track has by coincidence a neutral position at time equal 0.1 s. Moving forward from this time, the main component of Ω is in the y-axis with a smaller component in the z-axis. The particle therefore has main rotation along a horizontal axis perpendicular to one side, but also has some rotation along a vertical axis. The last axis picks up more rotation decreases - the particles starts to rotate over a new axis. The rotational vector turns more in the negative x-direction. The mean velocity of the particle has considerable variation and a mean velocity of about 52 mm/s. Other tracks show many different variations of this pattern where the dominant axis of rotation changes continuously changes to being roughly perpendicular to different faces of the cube. The current tracks and number of tracks are too short to gain a full description of the full dynamics of the falling cube.

Series of two identical particles released with a short distance have been measured for all three types of particles. For the cube and the rod, the effect of being in the wake of another particle in not very clear.



Figure 4: Rectangular cuboid: the angular motion around axis indicated in figure 2 and the vertical component of the velocity (positive downwards).



Figure 5: Short rod: the angular motion around the longest axis of the particle and the vertical component of the velocity (positive downwards).



Figure 6: Cube: the components of the rotational vector Ω from neutral to current orientation together with the vertical component of the velocity (positive downwards).

It is necessary to conduct a larger amount of series to make conclusions. For the flat rectangular cuboid, there is a clear effect. Figure 7 show variation of angle and velocity for two rectangular cuboids where one is moving in the wake region of the other. The second particle shows larger variation in the angular motion and periods with higher speed. The result is that the second particle catches up with the first particle if the particles are close enough. In general, this distance seem to be about 75 mm in vertical direction. This effect illustrated for a series of particle pairs in figure 8. Two rectangular cuboids are hold in the water with two pairs of tweezers and is then released simultaneously with a vertical distance of about 75 mm. Figure 8 shows mean difference in vertical velocity component (positive in downwards direction, second particle speed) as a function of the average vertical distance between the particles. Each observation has been colored by the average horizontal distance shorter than 10 mm is not shown since particles here tend to overlap in a part of the track. There is a significant variation in the vertical velocity difference, but also a clear trend for increased velocity of the second particle with shorter distance to the first particle. From visual inspection and from figure 7, this seems to be not only a simple wake effect, but also that the second particle is stimulated to have stronger periodic oscillations.

4 Discussion and conclusion

The suggested method for tracking both position and orientation of particles with regular shapes, in this case different cuboids, has been demonstrated to work well for the selected tracks. The data can give quantitative results for the dynamics of non-spherical particles under free fall. It is clear that changes in the orientation of the particle is closely coupled to the resulting velocity and that the velocity has a large variation. There is also, for at least one of the investigated shapes, a strong effect of being in the wake of another particle. The method can therefore be used to establish data for complex shaped particles and possibly use these results to improve models for particles forces for numerical simulations. Larger data series and longer tracks are need to get more solid statistics.

The detection of the particle orientation is not successful for all cases. As mentioned earlier, detection can be disturbed by e.g. small air bubbles on the windows. For different reasons, some tracks do not satisfy our criteria for matching the detected contours or for continuity in the development of the rotation of the particles. The algorithm therefore needs further development to become more robust. This can both



Figure 7: Two flat rectangular cuboid particle move close to each other. Particle 2 is in the wake of particle 1 with a vertical distance of about 36 mm. The angles show the angular position a long an axis parallel to the long sides and velocity is the vertical velocity component (positive downwards).



Figure 8: A flat rectangular cuboid particle moves in the wake of another particle with the same shape. The difference in mean vertical velocity component is plotted vs. the mean vertical distance between the particles. The color shows the horizontal distance between the tracks from 0 mm (dark blue) to 25 mm (yellow).

involve improvement of the optimization process finding particle orientation and in the use of data from neighbouring particles.

A further development will involve handling of overlapping particle shadows. Some information of the exact contours are lost during overlaps of particle shadows. The strategy, to be investigated here, is to use information of other time steps to compensate for the information lost due to overlaping particles. The issue will also be addressed by adding more cameras to the setup.

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