

Irregular plastic particles settling in non-quiescent water

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ABSTRACT

A new method for tracking both the velocity and the orientation of irregular particles that settle in water is tested for several plastic particles. The method uses a stereoscopic setup with two cameras and uses background illumination to create shadow images of the particles. The particle three-dimensional shape has been found in a separate scanning. Artificial shadow images are generated as a function of position and orientation. This is used in an optimization process to estimate the physical position and orientation. An experimental setup was developed to test both quiescent and turbulent conditions. Different particles have different settling models with motions that involve rotation or oscillation of the particles. Measurements on a small sample (six particles) indicate that while many particles were relatively insensitive to turbulence, some particles have settling modes that are significantly influenced by turbulence.

1. Introduction

Recycling plastic waste often requires separation into different types of plastic. The plastic sorting company Trebo has developed a method in which products composed of multiple types of plastic are granulated and then sorted in a sedimentation based process. Granulated plastic particles have highly irregular shapes, see examples in figure 1. The sorting process is based on material density, as this directly influences the particle settling velocity. However, the settling velocity is also sensitive to the size and shape of the particles and to the surrounding flow conditions. There are many available correlations for the drag coefficient for irregular particles (Michaelides & Feng, 2023), but they have significant errors in predicting the average drag force, typically in the order of 20% (Eberhard, 2026). Only a few correlations handle the particle orientation. The instantaneous drag force has a much higher variation, in part because it depends on the exposed cross section, which again depends on particle orientation.

The flow in a sorting process can be modeled using CFD-DEM that combine the Discrete Element Model (DEM) with Computational Fluid Dynamics (CFD), see e.g. (Ma et al., 2022). The link between DEM and CFD is the drag force of the particles. Almost all drag correlations are based on

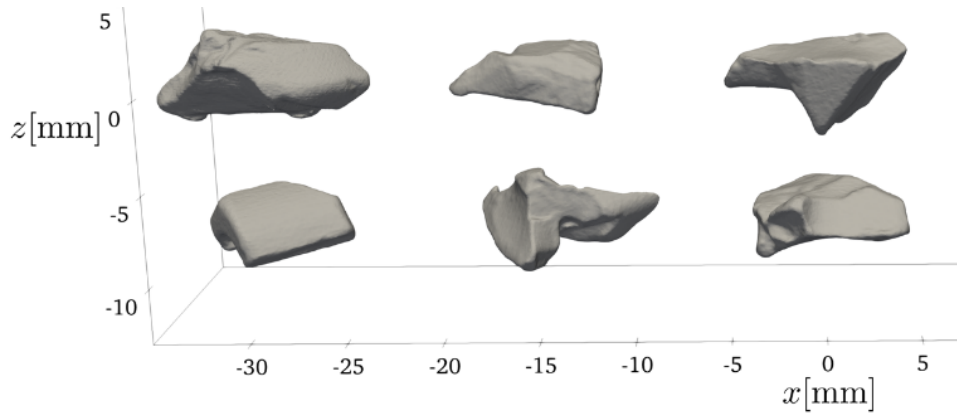


Figure 1. Particles used in the current study, reproduced from Eberhard et al. (2025). Particles are numbered P1 to P6 from left to right, top to bottom.

measurements in a quiescent fluid. Particles moving in a cloud of other particles will experience a turbulent environment. The objective of the present study is to test whether particles settling in turbulent conditions behave differently than particles settling in a quiescent conditions.

2. Experimental setup

The present paper presents measurements of plastic particles that settle in a water column. The particles are from a waste product made (among other materials) of POM (polyoxymethylene). The product has been shredded into pieces that have irregular shapes. We use particles sorted to a size (longest length) of about 10 mm. The particles are very irregular. A small part of the surface of the particles is the original product surface in the form of plane or curved smooth surfaces, whereas most of the surfaces are created from shredding. These are rough irregular surfaces with relatively sharp edges. Examples of six different particles are shown in figure 1. Data for the particles are shown in table 1.

The experiment uses a water-filled glass chamber with internal dimensions $200 \times 200 \times 800$ mm, see fig. 2. Two cameras are placed in the same horizontal plane with 90° angle between the optical axes. The optical axes are perpendicular to the chambers glass walls. The cameras are Basler a2A1920-160umPRO equipped with Edmund Optics 33304 lenses with a focal length of 16 mm using an F-number of $f/11$ to ensure the needed depth of focus. The total height of the measuring volume (aligned with camera width) is approximately 300 mm extending from near the bottom of the chamber. Softbox lights are placed opposite the cameras to provide background illumination. The light sources in each softbox are one Godox SL-60 and one Godox SL-100 which are 60 and 100 watt continuous LED lights, respectively. The softbox houses two layers of diffusion fabric such that the brightness is even across the plane facing the cameras. A frame rate of 60 fps is used, resulting in the largest particle rotation between frames being approximately 20° . An exposure

Table 1. Particle parameters: mass m , particle density ρ_p , longest, intermediate and shortest extent of particle L_L, L_I, L_S , volume equivalent diameter d_V in μm . Results shows are: mean vertical velocity $\bar{w}$ in mm/s, standard deviation of vertical velocity σ_w in mm/s and Reynolds number Re_p based on $\bar{w}$ and d_V . Data from Eberhard et al. (2025).

No.	m [g]	ρ_p [kg/m^3]	L_L, L_I, L_S [mm]	d_V	$\bar{w}$	σ_w	Re_p
P1	0.1578	1420	11.4, 6.9, 5.3	6.0	133	12	839
P2	0.1064	1420	8.4, 6.5, 3.2	5.2	131	4	725
P3	0.1193	1423	9.8, 5.7, 5.2	5.4	121	15	692
P4	0.0901	1441	8.0, 7.9, 3.8	4.9	108	10	563
P5	0.0981	1444	10.1, 7.8, 4.9	5.1	126	17	675
P6	0.1352	1441	8.6, 7.2, 4.0	5.6	118	23	706

time of 1600 ms is used.

To create turbulence in the water-filled glass chamber, a mechanism was designed to move a grid through the water column at a constant speed. The grid is made of rods with a square cross section with side length of 3 mm and a pitch of 18 mm. The grid thus has square openings of 15 mm by 15 mm. The openings next to the chamber wall are open towards the wall. The grid is moved with a velocity of 100 mm/s. This speed is similar to the settling speed of the particles. For measurements with turbulence, the procedure is to move the grid from the top to the bottom of the chamber and then release the particle at the top of the water column about 3 s after the movement of the grid started. To quantify the turbulence created by the grid, PIV measurements are performed with a laser sheet from 1.5 W continuous light laser. Laser sheet thickness is 1.5 mm and polyamide particles with a diameter of 20 μm is used as tracer particles. Single frame pictures are recorded with one of the Basler a2A1920-160umPRO cameras oriented with the width aligned with the chamber width. A framerate of 20 Hz is used. Data are processed with Dantec DynamicStudio ver. 8.5. The vertical velocity component after the grid has a small upward motion near the walls and a small uniform downward velocity of about 0.00018 m/s in the center of the cross section ($-75 \text{ mm} < x < 75 \text{ mm}$ and $-75 \text{ mm} < y < 75 \text{ mm}$). In this region, the standard deviation of the vertical velocity component w is shown as a function of time in figure 3. At the time when a particle passes, the standard deviation is about 0.002 m/s. This is 15%-20% of the particle settling velocity.

Data processing is done with custom Python software based on OpenCV (Bradski & Kaehler, 2008), the differentiable programming library PyTorch (Paszke et al., 2019) and several other libraries. The method is called Particle Tracking of Orientation and Velocity, in short PTOV. A full description is available in Eberhard et al. (2025). The processing is based on shadow images of the particles. First, a simple particle tracking is done in three dimensions. The particles were scanned in three dimensions in a separate process. Particle shadow images are then generated at different

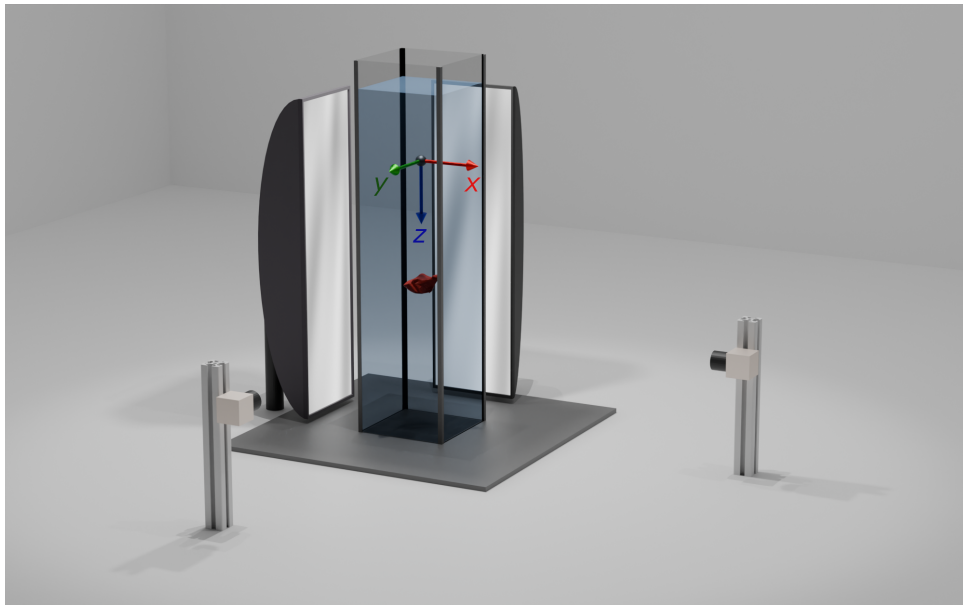


Figure 2. Experimental setup. The particle is drawn oversized for clarity.

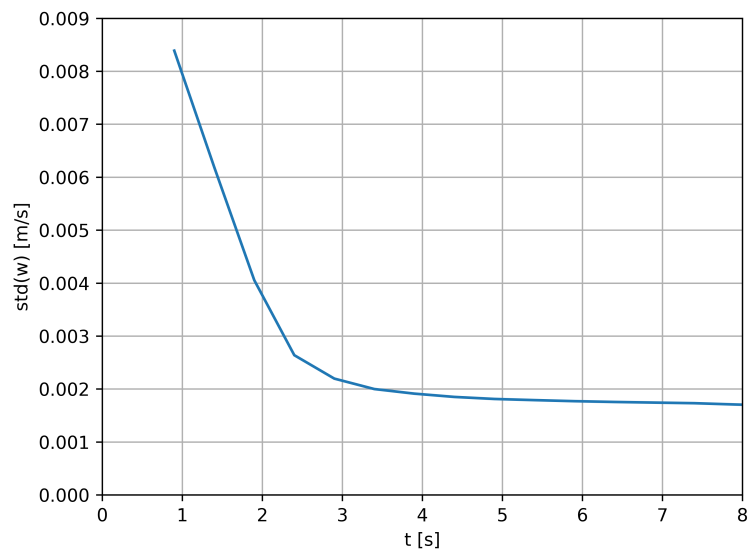


Figure 3. Standard deviation of vertical velocity component w as a function of time t after the grid has passed.

orientations of the particle and matched with the recorded image. This is an optimization process that results in both the position and orientation of the particle. These are collected to a track where velocities can be extracted.

The stereo camera system is calibrated using OpenCV's chessboard pattern tools. Intrinsic calibration is performed using 12 independent poses per camera, followed by extrinsic stereo calibration using 12 simultaneous poses to determine the relative geometric relationship between the two cameras.

3. Results

The six particles were first measured settling in quiescent water. The particles are released by hand at the top of the water chamber, and then the camera recording is started.

Selected tracks are shown in figures 4 and 5. For each particle, three plots are shown. The first shows the track projected to the x - y plane. The beginning of a track is moved to $(x, y) = (0, 0)$ and is marked with a black dot. The second plot shows the vertical velocity component w on the x -axis and the vertical position z on the y -axis. The velocity component w has been normalized with the mean value w_{mean} of w calculated for each track. The last plot shows an indicator for the orientation of the particle: the z -component of the $\mathbf{p}$ vector. The vector $\mathbf{p}$ is a unit vector attached to the particle so that it points upward for the orientations of the particles shown in figure 1. The particles are oriented here so that the largest cross-sectional area is perpendicular to the z -axis. When this vector is projected on the z -axis, the result is the component in the z -direction p_z . A value of 1 means that the particle is oriented as shown in figure 1. A value of -1 means that the particle is upside down. Values between -1 and 1 mean that the particle is rotated over a horizontal axis to an intermediate orientation. In the plot, p_z is plotted on the x -axis and the vertical position z is plotted on the y -axis.

Particle P1 (figure 4, top) shows rather random paths in the x - y plane. The vertical velocity component has a significant variation of approximately $\pm 25\%$ of the mean value. The value of p_z fluctuates semi-periodically from -1 to 1. This indicates a tumbling motion with rotation over several axes. Particle P3 (figure 4, bottom) has a similar behavior. Particle P2 (figure 4, center) moves in a circular pattern in the x - y plane. The vertical velocity is almost constant and the orientation is fixed with a constant value of $p_z = 1$, which indicates that the particle only rotates along a vertical axis. The particle is on a spiraling path down the water column. Particle P4 (figure 4, top) moves almost linearly in the x - y plane. The projected trajectory is slightly curved and is overlaid with small oscillations. The vertical velocity w has significant oscillations of up to $\pm 20\%$ of the mean velocity. The value of p_z oscillates near a value of 1 with a small amplitude. Closer inspection of the orientation shows that it oscillates over the axis aligned with the longest length of the particle. The motion patterns of the settling particles have been characterized by several studies, e.g.

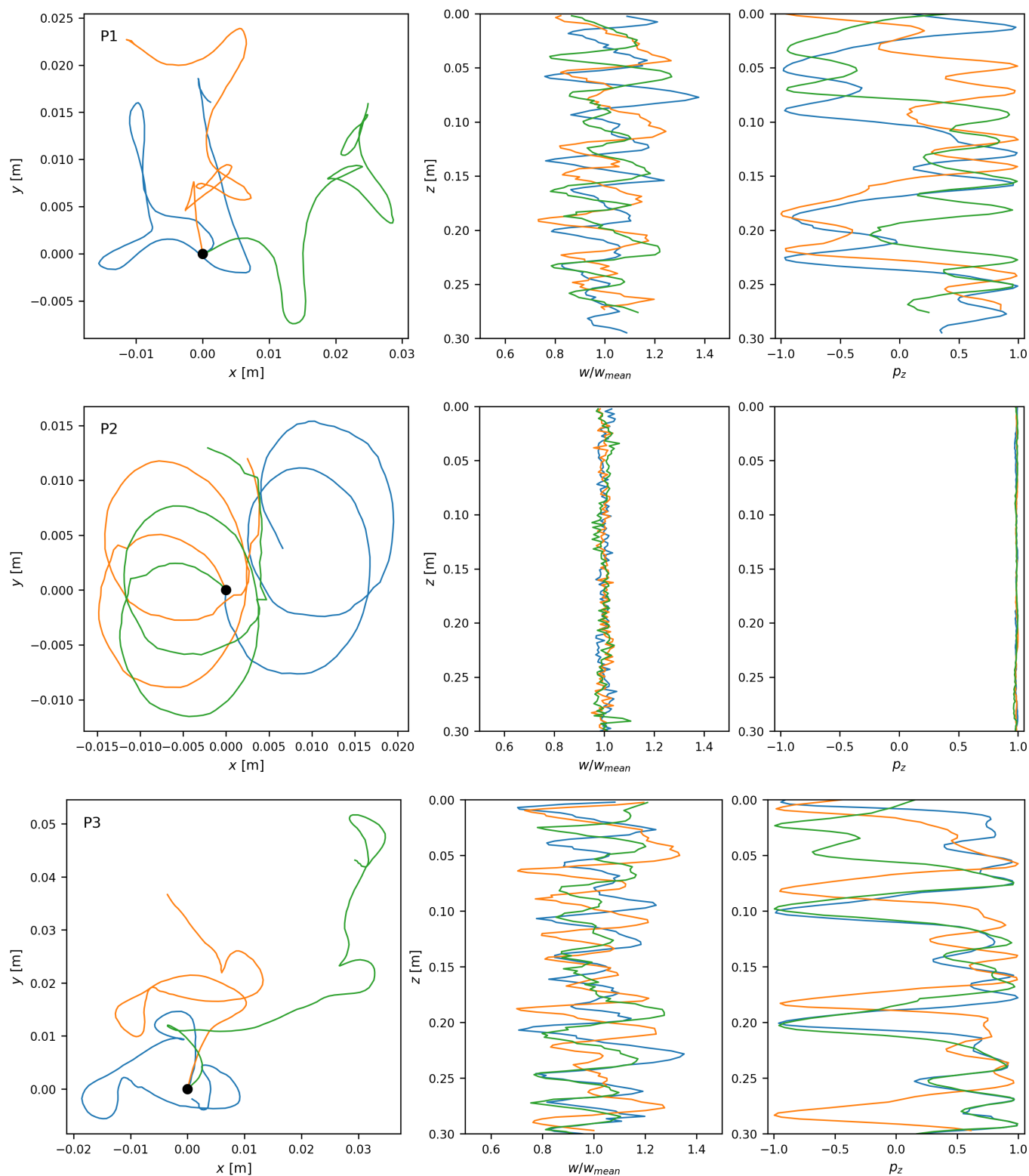


Figure 4. Selected tracks for particle P1, P2 and P3 (top to bottom)

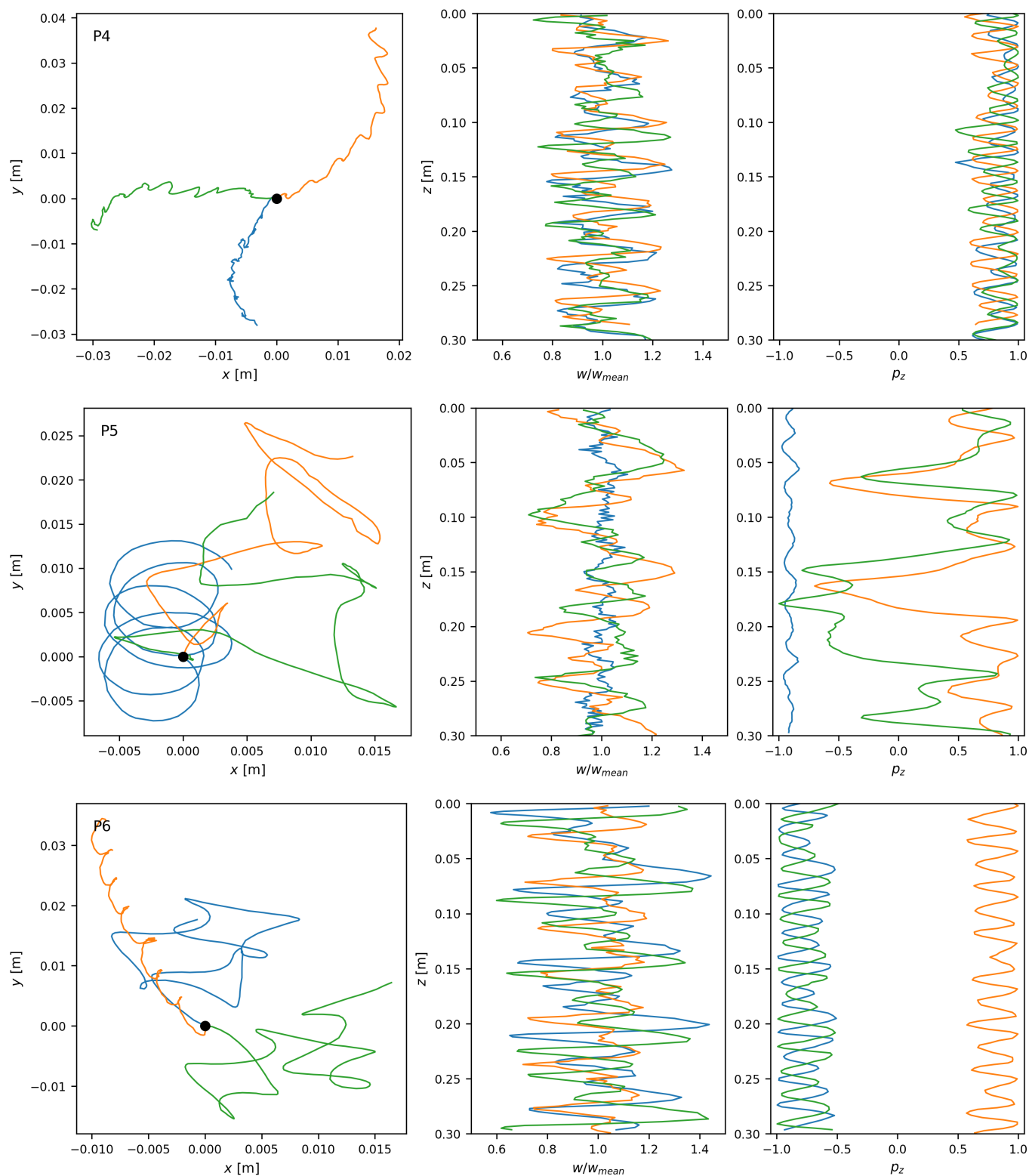


Figure 5. Selected tracks for particle P4, P5 and P6 (top to bottom)

Mandø & Rosendahl (2010). Most studies look at regular particles. The motion we have observed for irregular particles tends to be more complex. We have suggested names for the motion patterns observed in the present study in table 2.

Table 2. Motion modes observed in the present study

mode name	motion	particle orientation	particle
spiral-glide	spiral	weak rotation over vertical axis	P2, P5
wobble-glide	near linear	weak oscillation over horizontal axis	P4, P6
complex	glide with sharp turns	rotation over all axes	P1, P3, P5, P6

For particle P5 and P6, we observe several motion patterns for each particle in figure 5. Particle P5 can have both spiral-glide mode (shown in blue) and complex mode (shown in orange and green). Particle P6 can have both the wobble-glide mode (shown in orange) and the complex mode (shown in blue and green). The particles in the experiments were released in different initial orientation. No clear patterns between orientation and motion mode were observed.

To investigate the influence of turbulence on motion modes, about five drops were made for each particle under both quiescent and turbulent conditions. For particles P1, P2, P3, and P4, no significant changes in motion patterns were observed between quiescent and turbulent conditions, except for oscillation tending to be larger under turbulent conditions. For particles P5 and P6, about 25 drops for each particle were made under both quiescent and turbulent conditions to test if the distribution between the two motion patterns observed for each of the particles would change. The modes are determined by manually inspecting the results of each drop. The results are summarized in table 3.

Table 3. Distribution of motion modes for particle P5 and P6

condition	P5		P6	
	spiral-glide	complex	wobble-glide	complex
quiescent	52%	48%	50%	50%
turbulent	22%	78%	28%	72%

For both P5 and P6 under quiescent conditions, the complex mode is found in about 50% of the drops. In turbulent conditions, this increases to about 75%. The random motion in the turbulent flow seems to change the calmer modes to a complex mode. It should be noted that the setting velocity for the complex mode is on the order of 30% faster than the calmer modes.

4. Discussion and Conclusion

A new method for tracking both the velocity and the orientation of irregular plastic particles has been successfully tested. The measurement conditions were not always optimal. One factor is small air bubbles on the windows or small bubbles that rise in the water column from the bottom of the chamber. Another factor is the illumination of particles from the softbox perpendicular to the viewing axis of a camera. The method handled such challenges acceptably. However, the data processing has a number of adjustable technical parameters and these can be further optimized in future work.

The presented measurements should be considered a first study to test the feasibility of the measurement technique and of the dynamics of irregular particles. A large measurement series with more particles and more drops of each particle is needed to provide more solid conclusion on particle settling modes, physical mechanisms related to settling, and sensitivity to flow conditions like grid generated turbulence.

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