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Characterizing material flow in sensor-based sorting systems using an instrumented particle

Charakterisierung des Materialflusses in sensorgestützten Sortiersystemen unter Verwendung eines instrumentierten Partikels

Abstract: Sensor-based sorting is a well-established single particle separation technology. It has found wide application as a quality assurance and control approach in food processing, mining, and recycling. In order to assure high sorting quality, a high degree of control of the motion of individual particles contained in the material stream is required. Several system designs, which are tailored to a sorting task at hand, exist. However, the suitability of a design for a sorting task is assessed by empirical observation. The required thorough experimentation is very time consuming and labor intensive. In this paper, we propose an instrumented bulk material particle for the characterization of motion behavior of the material stream in sensor-based sorting systems. We present a hardware setup including a 9-axis absolute orientation sensor that is used for data acquisition on an experimental sorting system. The presented results show that further processing of this data yields meaningful features of the motion behavior. As an example, we acquire and process data from an experimental sorting system consisting of several submodules such as vibrating conveyor channels and a chute. It is shown that the data can be used to train a model which enables predicting the submodule of a sorting system from which an unknown data sample originates. To our best knowledge, this is the first time that this IIoT-based approach has been applied for the characterization of material flow properties in sensor-based sorting.

Keywords: sensor-based sorting, instrumentation, motion analysis, signal processing, flow control

Zusammenfassung: Die sensorgestützte Sortierung ist eine etablierte Einzelpartikel-Trenntechnik. Sie wird vielseitig als Qualitätssicherungs- und Sichtprüfansatz in der Lebensmittelverarbeitung, im Bergbau und im Recycling eingesetzt. Um eine hohe Sortierqualität zu gewährleisten, ist ein hohes Maß an Kontrolle über die Bewegung der einzelnen im Materialstrom enthaltenen Partikel erforderlich. Es existieren mehrere Systemauslegungen, die auf eine bestimmte Sortieraufgabe zugeschnitten sind. Die Eignung einer Auslegung für eine Sortieraufgabe wird jedoch durch empirische Beobachtung beurteilt. Die hierfür erforderlichen Experimente sind sehr zeitaufwendig und arbeitsintensiv. In dieser Arbeit stellen wir ein instrumentiertes Schüttgutpartikel zur Charakterisierung des Bewegungsverhaltens des Materialstroms in sensorgestützten Sortiersystemen vor. Wir entwerfen und realisieren ein Hardware-Setup, das u. a. einen 9-Achsen-Absolut-Orientierungssensor enthält, der zur Datenerfassung auf einem experimentellen Sortiersystem verwendet wird. Die vorgestellten Ergebnisse zeigen, dass durch weitere Verarbeitung dieser Daten aussagekräftige Merkmale des Bewegungsverhaltens extrahiert werden können. Als Beispiel erfassen wir Daten von einem experimentellen Sortiersystem, das aus mehreren Komponenten wie Schwingförderrinnen und einer Rutsche besteht, und werten diese aus. Wir zeigen, dass mit den Daten ein Modell trainiert werden kann, welches eine unbekannte Datenprobe der Komponente des Sortiersystems zuordnen kann, in welchem sie aufgenommen wurde. Nach unserem besten Wissen wird dieser IIoT-basierte Ansatz zum ersten Mal für die Charakterisierung von Materialflusseigenschaften in der sensorgestützten Sortierung angewendet.

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Schlagwörter: Sensorgestützte Sortierung, Instrumentierung, Bewegungsanalyse, Signalverarbeitung, Materialflusskontrolle

1 Introduction

Sensor-based sorting is a well-established bulk material processing technique from the field of machine vision that has found wide application in various industries. Typically, the goal is to purify a material feed by removing low-quality, foreign, or even potentially dangerous entities from the feed. Applications include the purification of foodstuff and agricultural products, e. g., the detection and removal of wheat kernels infected with fungal disease [1], raw materials and minerals [2], as well as the processing of solid waste [3] to prepare materials for recycling. Several system designs, which are tailored to the sorting task at hand, exist. A schematic overview of the workflow is provided in Fig. 1. Commonly, a material stream is perceived by one or multiple line-scanning sensors while being transported, for instance on a conveyor belt. The sensor data is processed with the goal of identifying individual particles contained in the stream and classifying those in order to derive an accept-or-reject decision. In many cases, pneumatic separation is used for the execution of this decision.

1.1 Problem formulation and contribution

There are two main types of errors that can occur during the sorting process. Firstly, an error in characterization of a particle contained in the feed can occur. In this case, the processing system makes a wrong decision whether a particle is to be accepted or rejected. Secondly, an error can occur during physical separation. This typically happens because of poor control of the actuator, i. e., the pneumatic separation. Due to the temporal gap between perception and separation, which is also visualized in Fig. 1, a hypothesis needs to be calculated when and where a particle will reach the separation stage. This in turn requires that all particles are accelerated to the same velocity with only small tolerance for deviations. Depending on the feeding and transport mechanisms, this can be a hard task for certain materials. In [4], for instance, nonuniform sliding speed of plastic particles with a rough surfaces on a chute is mentioned as a possible cause for a drop in yield.

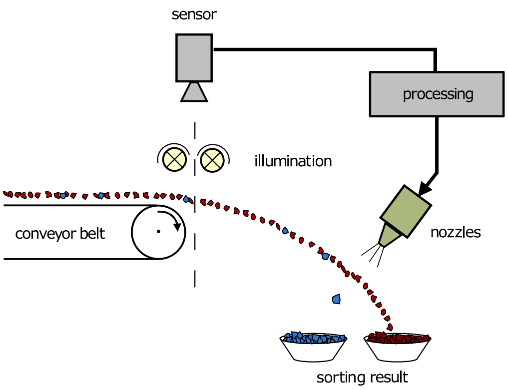


Figure 1: Exemplary scheme of a sensor-based sorting system. In this case, a conveyor belt is used for the transport of the material. Alternative designs include chutes or convey the material in free fall.

With respect to system design, the first type of error is tackled by choosing an appropriate sensor, possibly in combination with an illumination, as well as an efficient data processing system. In addition, the material may have to be prepared appropriately, for example by washing, scrubbing and drying. The second type of error, however, is mainly caused by imperfect motion behavior of individual particles contained in the feed. As of today, a common practice for choosing the appropriate transport mechanism, e. g., a conveyor belt, chute, or free fall, as well as its potential parameters, e. g., belt velocity, chute angle or fall distance, is by empirical observation. Obviously, the required thorough experimentation is very time consuming and labor intensive.

In this paper, we propose an instrumented bulk material particle for a quantitative assessment of the motion behavior throughout a sorting system. A product-like artificial bulk material particle is equipped with a system of small size including a 9-axis absolute orientation sensor which enables the acquisition of motion data. The approach has the benefit of being able to acquire motion data for the entire system without the need of information fusion or dealing with obstacles like occlusions, which would be the case for an optical assessment. In the course of the presented study, we introduce the hardware setup as well as the experimental sorting system used in an experimental validation. As a proof of concept, we demonstrate how the motion data can be used to identify the stage of the sorting process that the data originates from. Although the success of the approach is demonstrated on the example of sensor-based sorting, it can obviously be utilized in various scenarios of bulk material handling.

Table 1: Hardware components of the instrumented bulk particle.

Purpose	Type	Dimensions L × W × H in mm
Microcontroller	Adafruit Pro Trinket 3 V 12 MHz	38 × 18 × 4
9-DOF Sensor	Adafruit BNO055 Absolute Orientation Sensor	20 × 27 × 4
Data transfer	Adafruit Bluefruit LE SPI Friend (BLE)	23 × 26 × 5
Power supply	Adafruit Pro Trinket LiIon/LiPo Backpack Add-On	15 × 17 × 2
	LiPo Battery 3.7 V 100 mA h	20 × 26 × 4

1.2 Related work

Condition monitoring systems for structural health monitoring of buildings have received a high level of attention in the last years and reached a certain degree of maturity. In the rise of Smart Factories, Industry 4.0 and IIoT, instrumentation of hardware and systems also became a measure taken for industrial process control. With respect to bulk material handling and processing, a study on parameters to determine the technical condition of belt conveyors is presented in [5]. The authors present a condition monitoring system for belt conveyor idlers including temperature and vibration sensors. However, instead of monitoring a subsystem included in sensor-based sorting, we are interested in monitoring the flow characteristics of the feed. In geoscience, absolute orientation sensors are, for instance, included into gravel in order to gain insights into properties of particle transport in a stream during snowmelt period [6]. In [7], the authors present a "smart pebble" for environmental monitoring applications. Here, the instrumented particle consists of a memory module, sensor, processor, and power supply. The proposed design includes a tri-axial accelerometer and gyroscope sensor in order to obtain linear and angular displacements. An instrumented particle for experimental fluid dynamics research is presented in [8, 9]. Unlike flowability assessment methods purely based on optical systems such as [10], their approach also allows the acquisition of data for opaque or granular flows, for which optical systems are hard to implement, e. g., because of occlusions and the like. The latter also explains why optical systems appear inapplicable for material flow monitoring throughout a sensor-based sorting system. Although well adjusted sensor-based sorting systems have to avoid occlusions anyway while the material is perceived by the sensor and also during separation, this is not necessarily the case for all transportation steps. In our scenario, rather large areas need to be observed and occlusions can occur. Furthermore, the extraction of certain motion features, such as rotation, from image data can be rather error prone depending on the shape and texture of a particle.

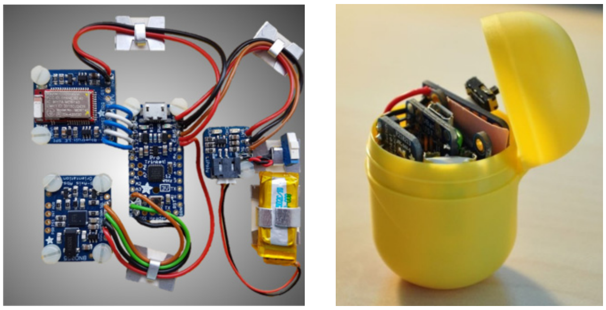
2 Methods and materials

In the following, we introduce the hardware setup of the instrumented bulk material particle and describe the sorting system and test product used for experimental validation.

2.1 Hardware setup of the instrumented bulk material particle

In order to gain information about the motion of an individual particle in the material stream, we design an instrumented bulk material particle including a motion sensor. For this purpose, we use the 9-axis absolute orientation sensor Bosch BNO055, which includes an accelerometer, gyroscope and a tri-axial geomagnetic sensor. The sensor can be used to measure the absolute orientation directed towards the earth's magnetic field. It allows outputting the orientation as unit quaternions which are numerically favorable over other representations. In addition, the sensor provides a calibration mode to further enhance the accuracy of the measurements. Furthermore, fusion algorithms are provided in order to calculate the absolute orientation values with consideration of the earth's magnetic field.

We create a setup to be able to read out and transfer the sensor data using a microcontroller and Bluetooth Low Energy (BLE) module. The components are listed in Tab. 1. The choice of components is mainly motivated by their low dimensions. In order to be able to integrate the setup into small bulk materials, the hardware setup should be as compact as possible. The resulting setup is shown in Fig. 2 and can be fit into a shell of approximately 35 cm^3 as shown in Fig. 2b. The selected microcontroller uses an ATmega328 onboard chip, which is also used in several Ar-



(a) Wiring of the hardware components.

(b) All components fit in a small shell.

Figure 2: Photos of the assembled hardware for the instrumented bulk material particle.

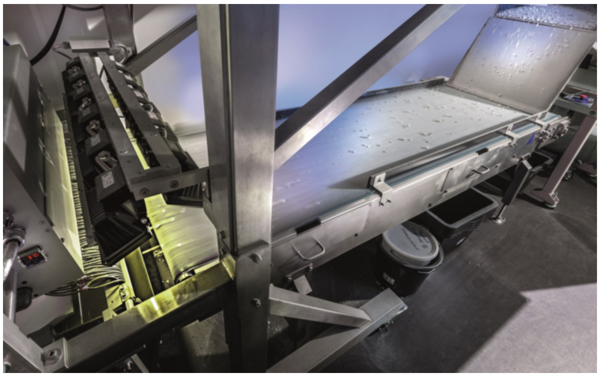
duino microcontrollers. It includes 28 KB storage and 2 KB of RAM and offers 18 GPIOs (general purpose input output) and 2 analogue pins. It can be programmed using a USB interface.

2.2 Experimental sorting system and test product

The experimental sorting system used for experimentation is shown in Fig. 3. Besides of the actual sorting compartment, which can be seen in Fig. 3b, it consists of several components for material transport that are typically found in bulk material handling and processing systems, e. g., several vibrating conveyor channels running at different frequencies, an ascending conveyor, a chute, and a conveyor belt. For running the experiments, it is particularly convenient that the material can be applied in circulation, which enables an easy collection of data.

The schematic illustration in Fig. 4 provides a segmentation into different components. Those are depicted in different colors. In the following, we will denote these components by the numbers used in Fig. 4 in brackets. We further define a starting area in which the measurement series begins. It is located on the vibrating conveyor channel (1) depicted in red, which can be seen in the center of Fig. 3c. From there, the material is transported to a smaller vibrating conveyor channel (2), which is shown on the left side of Fig. 3c and the right side of Fig. 3d. The material is then dropped and picked up (3) by an ascending conveyor (4), as can be seen in Fig. 3d. At the top, the material is again dropped (5) onto two additional vibrating conveyor channels (6, 7), where the latter feeds the material over a chute (8) onto the conveyor belt (9). The latter can be seen in Fig. 3b.

(a) Overall system.



(b) Sorting compartment.

(c) Vibrating conveyor channels.

(d) Ascending conveyor.

Figure 3: Photos of the experimental sorting system.

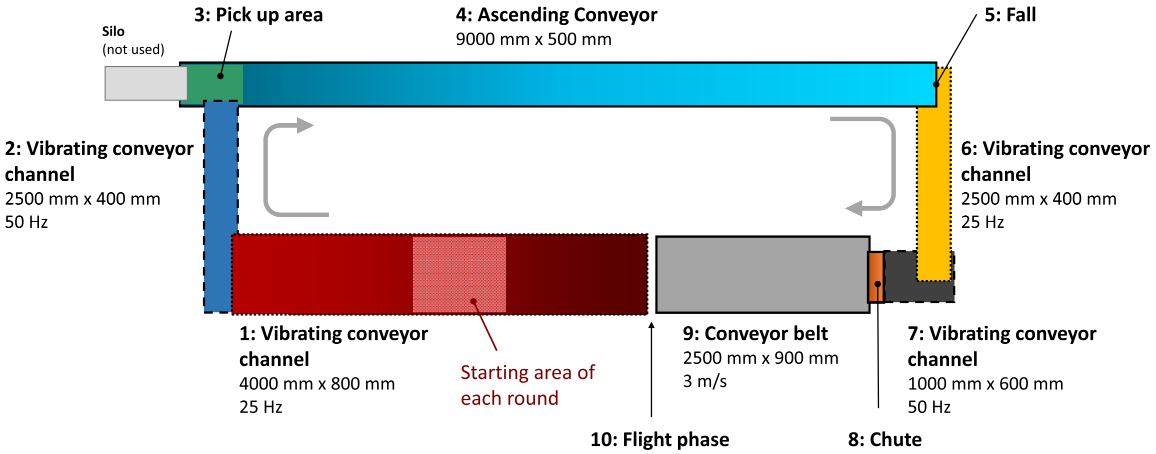


Figure 4: Schematic illustration of the experimental sorting system with segmentation into subsystems. For data acquisition, the feed is cycling through the system.

As a test product, we use marble pepples with particle size distribution 60 mm to 100 mm. Two samples can be seen in Fig. 5a. For the integration of the hardware, we design a particle made of polyoxymethylene (POM) that is similar in terms of weight, shape and size, see Fig. 5b. The hardware can be placed in the interior as can be seen in Fig. 5c. Except for the cavity inside, the artificial particle has a uniform density, which leads to a comparable moment of inertia.

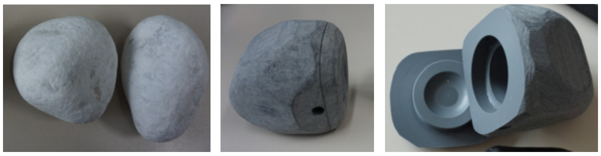

(a) **(b)** **(c)**

Figure 5: Photos of the test product and the host of the hardware: (a) marble pebbles, (b), and (c) shell for the hardware.

3 Experimental validation

In this section, we describe the experimental data that has been acquired utilizing the proposed approach and present experimental results for an exemplary classification task.

3.1 Data acquisition, preparation and processing

For data acquisition, we apply a stream of marble pebbles (as introduced in Sec. 2.2) including the artificial, instrumented bulk material on the sorting system. In each time step, the instrumented particle transmits a data packet containing a unique identifier, timestamp, acceleration in 3 dimensions, angular velocity in 3 dimensions, and orientation in form of quaternions. The frequency in which such data packets can be sent out depends on the size of the content. To increase the frequency, we exploit the fact that the motion sensor yields unit quaternions. Denoting quaternion q as

$$q = q_0 + q_1 i + q_2 j + q_3 k \tag{1}$$

with $q_0, \ldots, q_3$ denoting real numbers and i, j, and k the fundamental quaternion units, for a unit quaternion it holds that

$$|q| = \sqrt{q_0^2 + q_1^2 + q_2^2 + q_3^2} = 1. \tag{2}$$

This allows us to send only 3 of the 4 contained real numbers and reduce the fourth to its sign. We can then determine q_3 in a post-processing step:

$$\begin{aligned} q_3 &= \sqrt{|q|^2 - (q_0^2 + q_1^2 + q_2^2)} \cdot \operatorname{sgn}(q_3) \\ &= \sqrt{1 - (q_0^2 + q_1^2 + q_2^2)} \cdot \operatorname{sgn}(q_3). \end{aligned} \tag{3}$$

This improvement allows us to sent out data packets at a frequency of approximately 25 Hz to an app on a smartphone via BLE.

As an additional feature, we define the quaternion distance as

$$d_{\text{quat}} = \min(\arccos(s \bullet r), \arccos(s \bullet -r)) \tag{4}$$

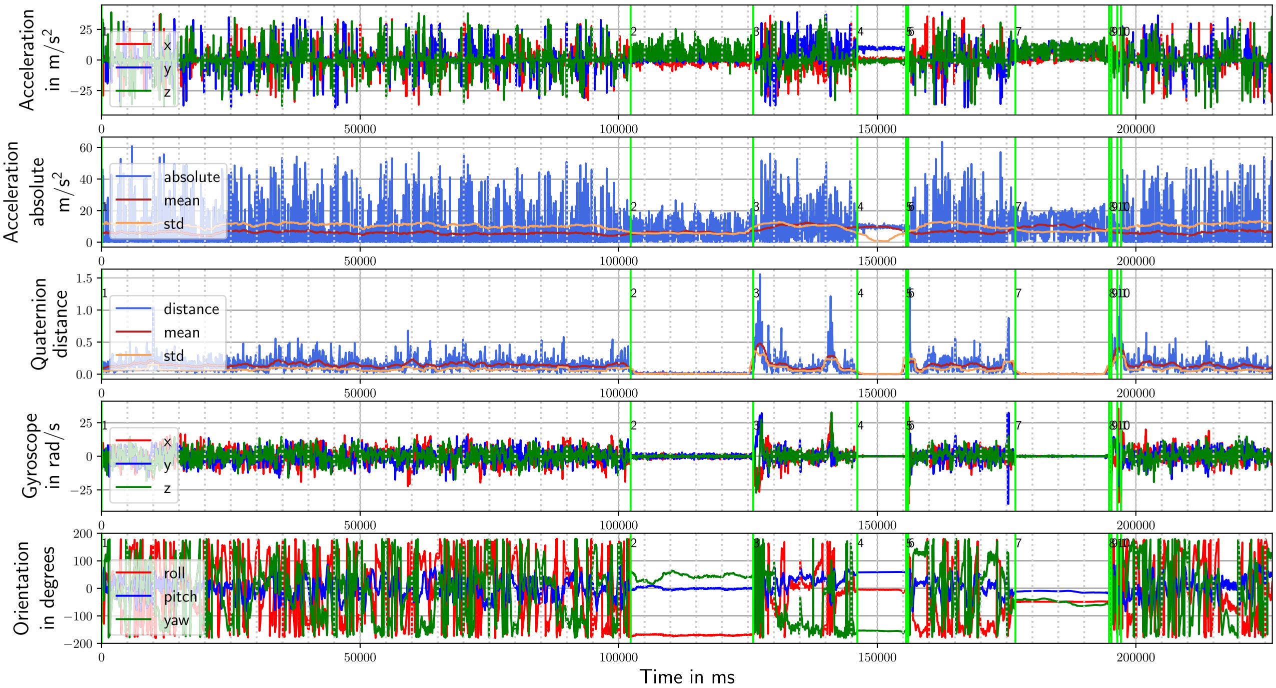


Figure 6: Acquired sensor data for one round on the system. As can be seen, the data can be segmented according to the different submodules of the system, as denoted by the green lines. The numbers correspond to the ones used in Fig. 4.

for two quaternions r and s and $\bullet$ denoting the dot product. It is important to note that q and $-q$ describe the same rotation. This distance as well as statistical measures (mean and standard deviation) are calculated offline after the data acquisition is complete.

An example of the resulting signals from one round on the sorting system, i. e., beginning at the starting area depicted in Fig. 4 and reaching there again, is shown in Fig. 6. In total, we record data for about 30 rounds. Using this visualization as well as timing information that has been logged during data acquisition, it is possible to manually segment the data according to the different components of the sorting system introduced in Sec. 2.2. In Fig. 6, the resulting segmentation is depicted by means of the green vertical lines and numbers corresponding to Fig. 4.

3.2 Preliminary results

In order to demonstrate the applicability of the approach for analyzing motion data on a sensor-based sorting system, we test the acquired data by training a classifier with the goal to predict the current submodule based on the motion data. We use 8 features for this purpose: the quaternion distance (as defined in Eq. (4)), inertial acceleration, and inertial velocity and all the corresponding means and standard deviations. The component of the sorting system from which a data sample was acquired serves as the label of the sample that is to be determined. For the classification task, we use an ensemble-based method, more precisely a random forest classifier. The presented results are obtained by training the classifier with the data from all acquired rounds but one, which in turn is the one used as the test set. As a measure of performance, we are interested in the ratio of data points for which the correct label, i. e., submodule, is predicted, which corresponds to the accuracy.

Figure 7 visualizes the results for the data presented in Fig. 6. The coloring of the different submodules corresponds to the one used in Fig. 4. As can be seen, for over 90 % of all data samples, the model is able to predict the correct submodule the data originates from. Minor errors occurring are distributed over all possible submodules. Therefore, it can not be concluded that the model performs particularly bad for certain submodules. These exemplary results can be considered representative for different test rounds.

4 Conclusion

In this paper, we presented an instrumented bulk material particle for measuring flow characteristics in sensor-based

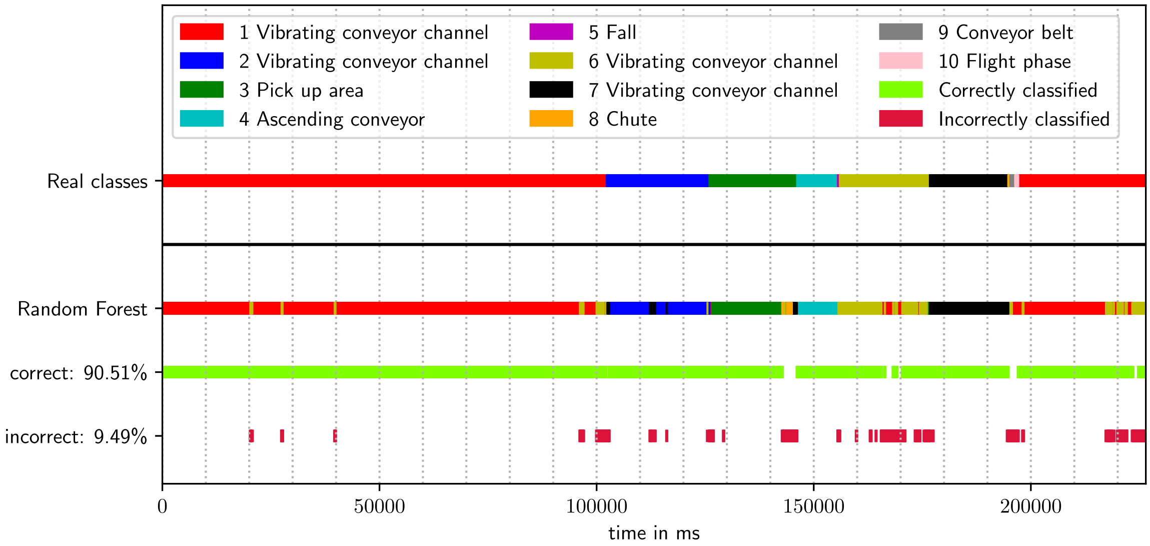


Figure 7: Visualization of the predictions of the model for the submodules of the data samples.

sorters. We designed and implemented a hardware setup containing a 9-axis absolute orientation sensor, which transmits the sensor data via BLE to a smartphone. We further designed and constructed an artificial marble pebble made of POM and placed the hardware in its interior. Motion data was acquired for several transportation rounds on an experimental sensor-based sorting system. We evaluated the data by means of the ability to determine which submodule an unknown data sample originates from. It has been shown that the data can indeed be used to train a model to perform this task.

In the future, we are interested in using the instrumented bulk material particle for optimizing system designs for specific sorting tasks. Also, we intent to acquire data for several instrumented bulk material particles simultaneously and use the data for evaluation of the variability of motion patterns.

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References

1. Floyd E. Dowell, Theodore N. Boratynski, Ronald E. Ykema, Alan K. Dowdy and Robert T. Staten. Use of Optical Sorting to Detect Wheat Kernels Infected with Tilletia Indica. *Plant disease*, 86(9):1011–1013, 2002.
2. Christopher Robben and Hermann Wotruba. Sensor-Based Ore Sorting Technology in Mining—Past, Present and Future. *Minerals*, 9(9):523, September 2019.
3. Janus T. Kirkeby, Harpa Birgisdottir, Trine Lund Hansen, Thomas H. Christensen, Gurbakhash Singh Bhander and Michael Hauschild. Evaluation of Environmental Impacts from Municipal Solid Waste Management in the Municipality of Aarhus, Denmark (EASEWASTE). *Waste Management & Research*, 24(1):16–26, February 2006.
4. Bastian Küppers, Sabine Schloegl, Gernot Oreski, Roland Pomberger and Daniel Vollprecht. Influence of Surface Roughness and Surface Moisture of Plastics on Sensor-based Sorting in the Near Infrared Range. *Waste Management & Research*, DOI: 10.1177/0734242X19855433, June 2019.
5. Xiangwei Liu, Yusong Pang, Gabriel Lodewijks and Daijie He. Experimental Research on Condition Monitoring of Belt Conveyor Idlers. *Measurement*, 127:277–282, October 2018.
6. James P. McNamara and Carter Borden. Observations on the Movement of Coarse Gravel using Implanted Motion-sensing Radio Transmitters. *Hydrological Processes*, 18(10):1871–1884, 2004.
7. Manousos Valyrakis and Edgars Pavlovskis. “Smart Pebble” Design For Environmental Monitoring Applications. In *International Conference on Hydroinformatics*, August 2014.
8. R. Zimmermann, L. Fiabane, Y. Gasteuil, R. Volk and J.-F. Pinton. Measuring Lagrangian Accelerations using an Instrumented Particle. *Physica Scripta*, T155:014063, July 2013.
9. Robert Zimmermann, Lionel Fiabane, Yoann Gasteuil, Romain Volk and Jean-François Pinton. Characterizing Flows with an Instrumented Particle Measuring Lagrangian Accelerations. *New Journal of Physics*, 15(1):015018, January 2013.
10. Joel Torres Serra, Joan Caba, Antonio Rodríguez Ferran and Enrique Edgar Romero Morales. Classifying Granular Materials for Feeding Performance using Experimental and Numerical Techniques. In *CHoPS 2018: 9th International Conference on Conveying and Handling of Particulate Solids*, pages 1–6, 2018.

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