with characters that can be written in multiple numbers of strokes which depends on the writer. In English, the average number of strokes is two strokes for uppercase letters and one stroke for lowercase letters. Cursive writing has an average of less than one stroke per letter[6].

Applications of OHWR systems vary across many domains. An OHWR system is useful for different users since it allows them to obtain the advantages of writing, with saving time by avoiding the scanning documents for digitization. Some applications are handwriting analysis in children[7], detecting alcoholism[8], and neurological analysis of patients[9].

For an OHWR system, a digitizer is required for the digitization process. Handheld devices such as tablets and smartphones recognize handwriting by following the location of the finger or stylus pen tip on the screen of the device. This has been successfully implemented in different applications but is constrained to the use of special writing surfaces. Gerth et al. [10] have shown that there are differences between writing on paper and writing on a tablet surface, where the latter requires additional movement control and presents a more challenging writing process. Therefore, to make recognition possible while writing on regular paper surfaces, devices with different sets of inertial measurement unit (IMU) sensors are required to track the movement of the writer's hand. This has been implemented in several applications that are discussed in the next section, yet the results are still not satisfactory to allow such systems to be used in real-world applications for real-time recognition systems.

When applying an OHWR system for real-world usage, different aspects should be considered for the system to be usable. One main requirement is that the system is simple to use, i.e no complex hardware with complex configuration needed. Another important aspect is that the system should work for all writers, that is, recognition should be writer-independent, and not trained for a specific writer. In this paper, we present a writer-independent system trained to recognize the Latin alphabet with the use of a sensor-enhanced ballpoint pen presented in Fig. 1. The recognizer requires no prior knowledge of the writer and can be implemented on a tablet for real-time recognition while writing on plain paper.

## II. Related Work

Over the past few years, several sensor-equipped devices have been designed and different approaches have been used to solve the task of real-time handwriting recognition.

In combining OCR with an IMU-based pen, Wang et al. [11] pursued the idea of using a trajectory reconstruction algorithm to estimate the position of the tip of a pen. The resulting trajectories were then classified by a regular optical digit recognition software on a tablet computer. They achieved a recognition rate of 94.6% for the ten digits.

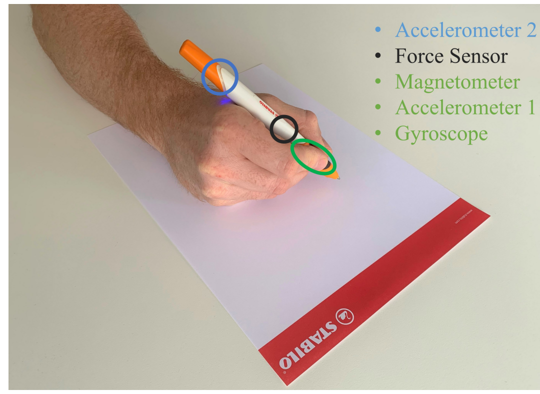


Figure 2. The location of the sensors on the Digipen [5].

Deselaers et al. [12] used gyroscope data from a mobile phone to trace an image of the hand movement while writing and used the produced image to recognize the written word following known offline writing recognition methods. They applied the system for single stroke movement of the device on the writing surface and presented the results showing the tracing accuracy of the hand movement.

Amma et al. [13] used a data glove to measure hand motion and extract gestures and characters drawn into the air. The tool was equipped with gyroscopes and accelerometers. They achieved a writer-dependent character recognition rate of 94.8% and a writer-independent rate of 81.9% using Hidden Markov Models. However, the complexity of the hardware with the process of writing in air posed a limitation for the usage of such a system as a recognizer application that can be used in regular daily situations.

Schrapel et al. [14] presented a sensor-equipped pen called Pentelligence. It senses the pen tip's motions and records the sound emissions when performing strokes. These data were used to train a Neural Network. They achieved accuracies of 78% (writer-independent) and 98% (writer-dependent) when classifying the ten digits.

Koellner et al. [15] used the Digipen by STABILO[1] to further pursue the research of online character recognition over 26 lowercase Latin letters with a collected dataset of 20,000 samples. A comparison is presented between LSTMs and other machine learning models for OHWR achieving 94% accuracy for writer-dependent classification, while showing a 52% accuracy for writer-independent classification, making the system inapplicable to be used for general recognition.

Summing up, different approaches have been taken to solve the problem of OHWR with different devices. However, various restrictions such as recognizing digits only, being user-dependent, or covering single stroke writing, and even using complex hardware limit the success of such systems in real-world applications. With such limitations,

[1] STABILO International GmbH (Heroldsberg, Germany)