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Chris Geiger*, Daniel Greff[3], Marcus Geimer[5]

Institute of Vehicle Systems Technology

Chair of Mobile Machines

Karlsruhe Institute of Technology

Rintheimer Querallee 2, Gebäude 70.04, 76131 Karlsruhe, Germany

Chris.Geiger@kit.edu

Michael Starke*, Martin Ziesak[4]

School of Agricultural, Forest and Food Sciences

Bern University of Applied Sciences

Laenggasse 85, 3052 Zollikofen, Switzerland

Michael.Starke@bfh.ch

Abstract: *To manage forest processes, information about the amount of timber that passed through different processing steps within the timber supply chain is essential. This information can be used both to keep the overview of the amount of timber already produced for initiating further activities and to clear accrued operation expenses promptly. When felling operations have been supported by or carried out exclusively through manual working steps, information sources like harvester protocols are either not available or lack sufficient accuracy for their proper use. To solve this problem in cut-to-length logging, a weight-detection system can be integrated into the loading process of the logs as single stems or stem bundles. This system can be used for estimating the timber volume moved, thus closing the information gap without further interactional effort. Unlike common crane scales, which are not available for every type of machine, the method presented here for a weight-detection system is universally applicable in modern crane types.*

In the first step of the development stage, loading processes during the work task of the forwarder are detected. Using an artificial neural network and data provided by the sensor set of a modern crane, the weight of the load in the grapple can be estimated based on the position of the grapple and the hydraulic pressure of the boom cylinder during these loading processes. The accuracy error of only 10% of the volume moved after initial training of the neural network demonstrates the potential *of this system. By obtaining more training data through further measurements, an accuracy error of less than 4% is expected. For decision making within the forwarding process, this technique can therefore be a reasonable solution for short-term and extensive implementation of the smart forwarding processes that are currently being established in the Forwarder2020 project.*

Keywords: forest management, process management, crane scale, weight detection, neural networks, Forwarder2020

1. Introduction

The logistical management of the timber supply chain offers high optimization potential to the forest industry (Heinimann 1999). Mainly due to the wide variety of forest actors' internal structures and their functions within the timber supply process, the information flow within the timber supply process can easily be interrupted, leading to unnecessary time delays which hinder the possibility of making adapted strategic economic decisions (Bodelschwingh 2006).

The main indicators exchanged in the information flow, particularly concerning the volume or weight of the moved or processed timber, are the characteristic numbers for a wide range of single processing steps. Consequently, various manual and automatic volume and weight measurement systems have been established in the past decades, for example to calculate own performance, gather information for process managing purposes in forest enterprises or answer scientific questions. Depending on their scope of application, the measurements may follow strict regulations if their estimated values have a legally binding character such as compliance with formal trade practices or safety regulations (European Parliament and Council of the European Union 4/29/2015) or, with lower accuracy, may simply serve as volume estimating assistance. For each objective, the desired accuracy or the possibility of official calibration of the measuring system can be crucial for its use. This classification of different systems, which can be given by official testing laboratories under national laws, considers national and international trade regulations and is often required for their accredited use by forest administrations (Landesbetrieb Landesforsten Rheinland-Pfalz 10/26/2017; Petty and Melkas 2013; ForstBW 2013).

2. Aim of development

When focusing on the automatic estimation of the timber volume moved during forwarding work in cut-to-length (CTL) operations, the volume information is not always available without supplementary equipment (Manner 2015). This emphasizes the as yet unsolved information deficit problem also presented in Bodelschwingh

2006. As an alternative solution, Manner (2016) suggests filling this information gap with additional data from harvester protocols and spatial information (ibid.). While not every felling operation is necessarily fully mechanized, direct measurement of the volume or weight while loading, unloading or measuring the weight being moved by the forwarder as loaded weight should be strived for in order to guarantee the highest coverage of CTL logging process variations.

Additional mounted crane scales, as used for the John Deere TimberLink™ system (John Deere 2014) or the PONSSE load optimizer (PONSSE 2018), currently provide common, highly accurate solutions that can also meet official measuring standards (i.e. ForstBW 2013). A case study conducted by Petty and Melkas (2013) in Finland showed the accuracy of these systems, where over 99% of the measurements tested achieved the in Finland required 4% weight tolerance with the use of six different scale manufacturers. This study even showed higher accuracies than previous measurements, further underlining the higher accuracy of crane scales based on hydraulic pressure as compared to strain gauge measuring principles (ibid.). As a functionality of most crane scales (Sebulke 2016; ForstBW 2013), it is possible for these systems to work in different measuring modes (automatic to static in mid- to high accuracy), and thus can also be used for continuous measurements with a lower accuracy during regular work or in semiautomatic mode, for example loading swap trailers (Korten and Kaul 2012).

Regarding dispositive issues in the supply chain, these products can, on the one hand, potentially meet requirements thanks to these different measuring modes because the automatic measuring mode does not influence the driver in his working behaviour and hence his work productivity. On the other hand, due to the additional costs of the extra modules which need to pay off directly for the user, these products are currently not extensively distributed in equal measure and are consequently only partially available for information exchange without high accuracy requirements.

The use of modern cranes enables a new possibility to access weight or volume information without additional equipment costs and offers the potential of establishing an informal source of information about the timber volume moved for comprehensive purposes.

With the crane's already equipped internal sensor set, accessible through the controller area network (CAN), it becomes possible to derive the lifted weight directly by calculating the force needed and the position of the crane. Although the movement of the crane as well as the oscillating movement of the lifted logs create a constantly changing weight value, weight estimation using dynamic payload detection, for instance as described in Hindman (2008), is possible. In this first study, this approach, including the use of two different artificial neural networks was tested on an old crane which had been manually equipped with the relevant sensors of a modern crane. The collected data was evaluated in a post-process to present the feasibility of this approach and the technical potential of the system.

3. Material and methods

3.1 Detection of loading cycles

For an automatic recording of log loadings, the individual loading cycles during the work task have to be detected and differentiated. Within one individual loading cycle, especially during the period when the log is picked up, it is possible to estimate the current mass of the grapple content. The identification of loading cycles can be achieved by a separate neural network (NN), which requires the joystick signals as well as the absolute position of the grapple as input data. The delivered output data is a vector specifying whether the grapple is currently loading a log or not. Individual loading cycles that correspond to a complete loading phase from the complete cycle data are thus generated. The network was trained using data from previous measurements and the accuracy was thoroughly examined through visual confirmation of the measurements evaluated (Geiger and Geimer 2017).

3.2 Theoretical functionality of weight detection

To enhance the project viability and to reduce implementation requirements, the number of sensors necessary to accurately generate reliable projections on the mass of the timber log under different loading conditions was minimized. In theory, precise knowledge of the grapple's positional data during a loading cycle as well as the time series of the pressure in the hydraulic cylinder is sufficient to develop a log balance. The position of the grapple is calculated using a kinematical model from the individual displacements of each hydraulic cylinder. This displacement was recorded in a laboratory using laser distance sensors. For the hydraulic pressure, only the inner boom cylinder was equipped with a pressure sensor. This sensorial data during the cycles along with the crane control signals were then pre-processed and used by the NN to estimate the payload mass.

3.3 Calibration and peripheral sensor preparations

The pressure sensor and position sensors were calibrated as they were mounted onto the machine. The positional sensors were parameterized using the minimum and maximum positions of the respective hydraulic cylinders. Furthermore, the forwarder had to be prepared specifically for the accurate recording of the laser signals. The swivel angle was recorded with a draw-wire sensor and its end was attached to the crane pillar. All analogue sensor signals and CAN signals (joystick signals) were recorded with a Micro Autobox.

3.4 Testing procedure

Before generating the data for the NN, appropriate logs had to be chosen to effectively represent the possible mass spectrum encountered in the forest during real operation. As such, ten logs with different masses were selected and recorded, while the tree trunks were simultaneously numbered. Prior to the actual test cycles, static measurements were taken to review the behaviour of the sensors under test conditions and to verify the functionality and plausibility of the individual sensors.

For each test cycle, the logs were loaded in random order and in a random combination of multiple- or single-log grappling. During these cycles, the logs were placed at random locations that the driver had designated beforehand. The driver was advised to emulate the position of tree trunks in the forest and place the majority at medium distances, but at times also pick up logs from a closer or further distance.

3.5 Data interpretation by the neural network

Data preparation for the NN was automated based on the previously implemented cycle recognition. However, to limit the size of input data, only the seconds around the moment when the grapple picks up the log were considered relevant input data. During the data preparation, the signals were filtered to remove white noise.

The pressure signal was treated differently: by filtering the original time series with varying window sizes, different resulting time series were generated. These varying windows sizes resulted in low- and high-frequency pressure signals that served as input data for the NN. Following the data preparation, subsequent time series were generated as input data:

(1) pre-processed pressure sensor signals, (2) positional data on the grapple, and (3) joystick signals.

The resulting time series for each loaded log were then divided into sections of equal size. Each section was represented by statistically derived indicators (e.g. mean, minimal and maximal pressure value of that section). The resulting data matrices of the respective masses of the logs were fed into the NN as a solution vector for each loaded log or as a combination of logs.

4. Results and discussion

As the accuracy of the results of the NN compared to its ideal output is directly proportional to the accuracy of the later assigned weight of the logs, this output can be directly used to evaluate the first test of this approach.

Figure 3 thus shows the normalized results of the NN for the different data sets of training data, validation data, test data as well as all data combined. Each graph displays the normalized target and output of the NN, given that the input data is normalized as well. Therefore, an optimal result of the NN matches the ideal output, visualized as the red, dashed line.

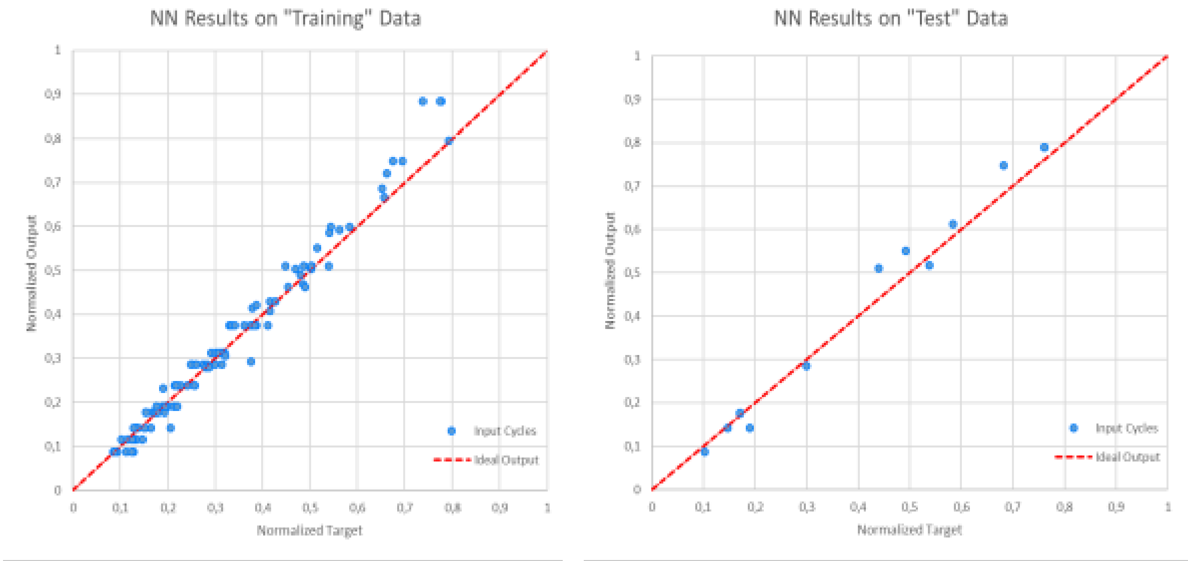

Figure 3: Results of the neural network

The results of the test data set indicate a very high accuracy of the presented method. Almost all of the input cycles, displayed as blue dots, are remarkably close to the ideal output. Although a sensor fault occurred during the measurements, the highest deviation in the test data is 24.2 %. Considering all test data, the mean accuracy is 9.1 %, which means that log masses can be measured correctly during the dynamic working process of a forwarder.

Higher accuracies on the predicted mass for the timber logs would be achieved by increasing the amount of input cycles, and thereby reducing the influence of outliers on the algorithm. The results presented, observed from the NN, suggest that the velocity and acceleration of the grapple arm movement, as potential disruptive factor for the training-effect of the network, play a minor role.

Therefore, this method is a promising and cost-effective way to accurately and reliably determine the mass of timber logs using a minimal number of sensors combined with a sophisticated neural network.

Summary

As for the objective to create a comprehensive tool to close the information gap of the timber volume processed, the current results offer a wide range of application possibilities in the forest industry, especially for lower-accuracy data collection. The implementation of this system as a post-processing application or as a potential real-time detection system in the prototype forwarder of the "Forwarder2020" project seems possible as a potential weight-detection system for future needs (HSM Construction 2016). The aimed requirements of less than 4% (conventional crane scale equivalent) on a legally non-binding base are expected to be met with further development and additional training data from future field testing.

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