*Article Identifier*
*DOI: 10.22032/dbt.58858*
*URN: urn:nbn:de:gbv:ilm1-2023isc-090:8*

*60th ILMENAU SCIENTIFIC COLLOQUIUM*
*Technische Universität Ilmenau, 4 – 8 September 2023*
*URN: urn:nbn:de:gbv:ilm1-2023isc:1*

# Investigation into the implementation of a multimodal 3D measurement system for a forestry harvesting process

*Illmann, Raik[1]; Fütterer, Richard[1]; Lummitsch, Sascha[2]; Rosenberger, Maik[1]; Notni, Gunther[1]; Findeisen, Erik[2]*

Technische Universität Ilmenau[1]
Fachhochschule Erfurt[2]

## ABSTRACT

In the context of digitalization, monitoring and traceability are also becoming increasingly important in the forestry sector. An essential component of the most efficient value creation is the recording of relevant characteristics right from the start. The optical and tactile recording of characteristics, such as diameter and volume, have been solved to a large extent in the harvesting of heavy timber, but differs significantly from that of small timber. This paper is about an investigation on the implementation of a multimodal 3D sensor system, which is used for the stable detection of biomass directly in the harvesting process of weak wood. System technical possibilities are shown how biomass can be determined directly during the harvesting process by means of multimodal 3D measurement technology. Considerations regarding possible measurement principles and methods result in two methods, which are discussed within this thesis regarding their advantages and disadvantages. The development stages are presented in detail up to the practical tests, which also includes the acquisition of empirical a priori information. Finally, data are determined by means of test scenarios, which prove the principle functionality and make the methods evaluable.

***Index Terms*** **–** 3D measurements; forestry measurements; multimodal imaging

## 1. Problem description

For the harvesting of weak wood with a breast height diameter of 7-15cm, so-called cutting-and-accumulation units are used, which are often attached to the outriggers of diggers or agricultural machines. Figure 1 shows a typical representative with the unit "Woodcracker C" of the company "Westtech". During harvesting, the wood is separated with a cutting edge. The attached jaws make it possible to accumulate several logs into a bundle, which is then placed on a deposit pile. In harvester units for heavy timber harvesting, the measurement of the timber is state of the art and solved, whereas the measurement of the biomass is much more difficult in the cut-and-accumulate method. Up to now, the determination of the mass is done manually by measuring the formed deposits according to certain procedures [1]. This also involves determining the diameter of individual logs and extrapolating the corresponding biomass using correlation tables. This is very time-consuming and also inaccurate. Weighing the entire mass as it is transported provides a means of determining mass, but at the expense of traceability. For upcoming forestry harvesting and planning procedures, it is quite useful to be able to determine the vegetation georeferenced. In general, monitoring is one of the most promising tools for optimizing forestry processes.

*Figure 1: Cutting-and-accumulation unit "Woodcracker C" of the manufacturer "Westtech".*

Under these boundary conditions, the question thus arises as to how the biomass can be determined during the harvesting process itself. Weighing the mass accumulated in the aggregate is also possible, but is clearly too inaccurate and unstable due to the many force shunts (hanging wood, etc.). A non-tactile probing of the measured objects with optical systems forms the basic concept of the present study. The further use of spectral measurement technology would also offer the possibility of acquiring other relevant information. These include, for example, moisture, fungal infestation, chlorophyll content or characteristics helpful for determining the tree species. However, these approaches are not discussed in more detail in this paper.

## 2. Theoretical considerations for the problem solution

The constraints described at the introduction make high demands on a technical system that is to capture data without contact using optical measurement technology. In a first development stage, variants for the measurement process were designed which, in terms of arrangement and robustness, can enable optically supported measurement under the given requirements. Figure 2 shows the results of the conceptual variants for the measurement process, which can serve as a basis for the further development steps. When developing these variants, in addition to the prevailing conditions and requirements (environment, mechanical stresses, etc.), intervention in process times and cycle times was also discussed. Time gaps and dead times in the harvesting process were identified and included in the evaluation. There are essentially two ways of optical determination of the biomass in the harvesting process. The first variant refers to a direct measurement on the aggregate. This can be done either by an additionally attached kinematic system (Figure 2 left) or by a kinematic system directly integrated into the cutting edge of the aggregate (Figure 2 right). Other methods are based on indirect sensing from a greater distance. Thus, in principle, it is possible to probe the bundle from a distance or, as will be discussed later, to determine the negative by detecting the harvested area.

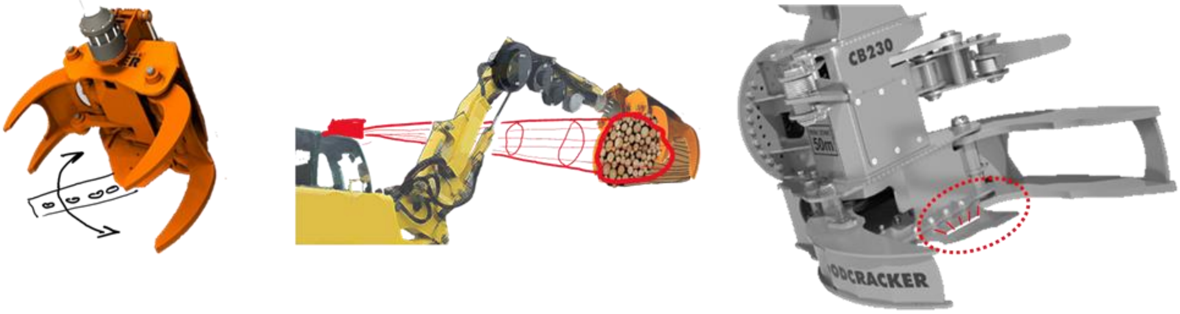


*Figure 2: Possible measurement methods.*

## 3. Evaluation of the measurement principles

In the first practical phase, suitable measurement principles were evaluated. Since these investigations were carried out under laboratory conditions, it was necessary to sift representative targets. The compilation of representative targets was based on observations and inspections of real application scenarios. Thus, a reference sample set was created, with a wide variety of light tree species processed using different separation methods (Figure 3).

*Figure 3: Representative measurement targets.*

In addition, the measurement arrangement was simulated and calculated with respect to possible resolution and geometries on the basis of real physical invariants, such as applicable working distances and object fields to be covered. The overall goal was to gain knowledge about the basic usability of certain sensors and sensor systems. Individual sensors and systems were tested on the basis of the samples for their general usability for the specified measurement scenario and evaluated with regard to their system interaction. For this purpose, a corresponding setup with different sensor systems, each of which follows different measurement principles, was implemented and put into operation. Active (no additional lighting required) and passive systems were set up and evaluated. In this way, additional important insights into the prevailing conditions with regard to lighting and disturbance variables could be gained at this point.

*Figure 4: Evaluation of measurement principles.*

A LIDAR system based on the "Intel-Realsense-system", a self-developed passive stereo system [2]and a combined setup consisting of a 3D-TOF (time of light) system and a high-resolution RGB color camera were tested. All three systems were used to acquire the representative sample setup in the front face. The results are shown in Figure 4. In principle, it could be shown that all three systems provide useful measurement results with respect to the measurement task. Figure 4 left shows the results of the "Intel-Realsense-system". This setup already contains a registered color camera, which is why the point clouds are already available with color information. The parameters of the system, which can be influenced by the operator, were varied in the laboratory to achieve the best possible result. However, it could already be determined during this preliminary investigation that the entire system is very sensitive to extraneous light. For this reason, this system is not suitable for outdoor use. The results of the passive stereo system are shown in the center of the Figure 4. This system is much more robust against instabilities such as intensity fluctuations, but a minimum illuminance must be ensured, otherwise the measurement principle itself does not work. With regard to the application, a sufficiently strong light source must be provided. The third system (Figure 4 right) is a combination of an active time-of-flight system and a high-resolution RGB camera (5 megapixels). The advantage over the "Intel-Realsense-system" is that the color information is not reduced to VGA resolution, but the high-resolution 2D image from the color camera is available in addition to the color 3D measurement values in VGA resolution. If we now evaluate the systems and results from the point of view, the third system was found to be the most suitable for outdoor use. It is also very insensitive to the effects of extraneous light, which can be well compensated by the appropriate choice of system parameters (e.g. exposure time). exposure time) can be compensated. Thus, for example, a can be prepared for daytime or nighttime use.

## 4. Conception of the measurement methodology and the evaluation algorithms

### 4.1 A priori information

Both methods discussed assume that the biomass is recorded in volume units from geometric data of the trees. For the measurement method of direct measurement at the aggregate, a clear description of the cross-sectional areas is available through the cross-sectional images. From this, diameters and surface areas can be determined. Possible measured variables for the calculation of biomass by indirect probing from a distance are the contours of the half-hulls and the heights of the trees.

*Table 1: Exemplary empiric data [3].*

| **probe number** | **height in m** | **number of branches** | **circumference tree base in cm** | **volume in ml** |
|---|---|---|---|---|
| **1** | 3,11 | 6 | 9,40 | 640,00 |
| **2** | 3,21 | 5 | 11,60 | 820,00 |
| **3** | 3,83 | 2 | 9,40 | 720,00 |
| **4** | 3,62 | 3 | 9,50 | 660,00 |
| **5** | 3,88 | 3 | 10,60 | 680,00 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

However, none of the measured quantities is sufficient to determine a complete volume. Thus, both methods require correlating variables that must be referenced to complete the necessary parameters. To obtain knowledge about this, the relationships between the characteristics such as volume, size and diameter were obtained empirically [3]. The volume was determined experimentally by displacement tests, all other sizes by measuring with length measuring techniques. Table 1 shows exemplarily some empirically determined data, which are (have to be) included as a priori information for both methods.

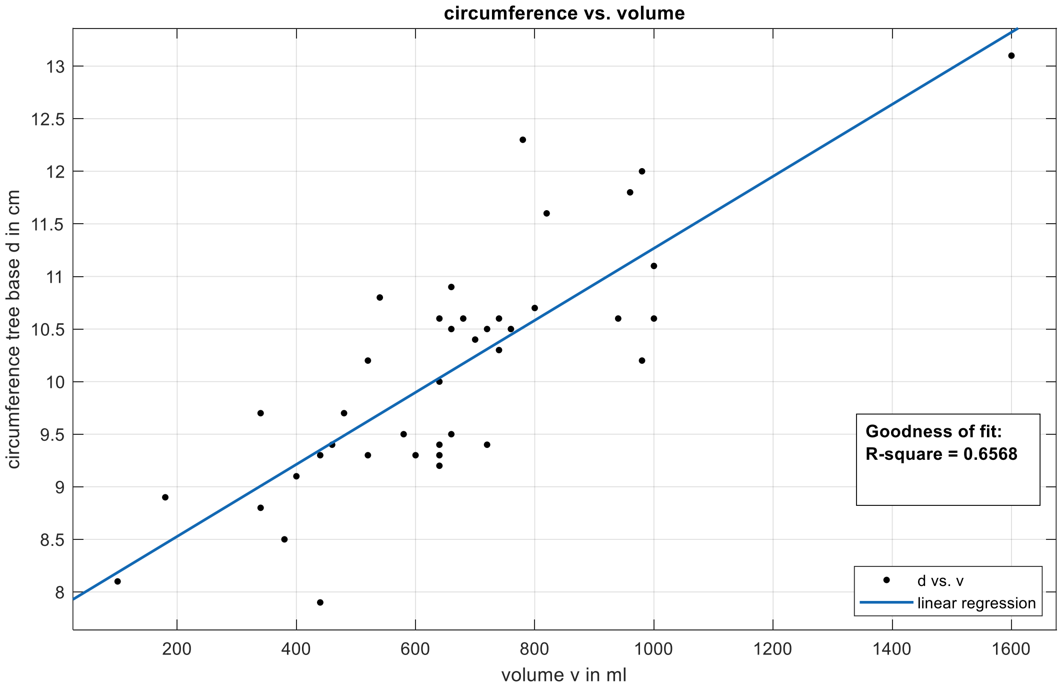


*Figure 5:Correlation between circumferences and volume.*

The tree species "Populus trichocarpa" of the hybrid cultivar "Fritzi Pauley" was examined for its parameters. All samples came from the same area, were examined on the day of felling and had a tree age of 2 years.

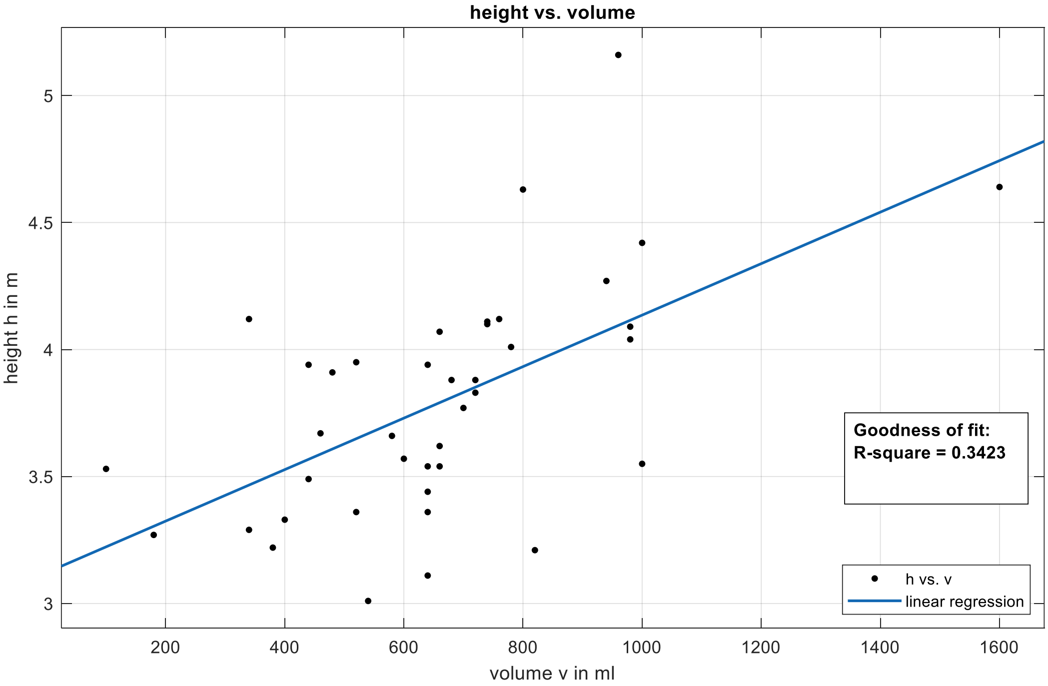


*Figure 6: Correlation between tree height and volume.*

The statistical evaluations shown in Figure 5 and 6. Figure 5 illustrates the relationship between biomass volume and perimeter. The regression degree shown is the result of a linear regression through the point cloud. The coefficient of determination R-square represents the so-called goodness of fit and describes how well the measured values fit the regression model. The closer this value is to 1 (100%), the better the model fits the initial data [4]. The regression model makes it possible to describe the empirical information analytically and to transfer it into a computational model, which can then be used for the approximation. Analogously, Figure 6 shows the relationship between tree height and volume. Qualitatively, both sets of data are suitable for drawing conclusions about biomass. However, the comparison of the scattering parameters clearly shows that the circumference at the base of the tree correlates much better with the actual volume than the height. At this point, however, it must be noted that this correlation may well be different for a different population (e.g.) coniferous wood.

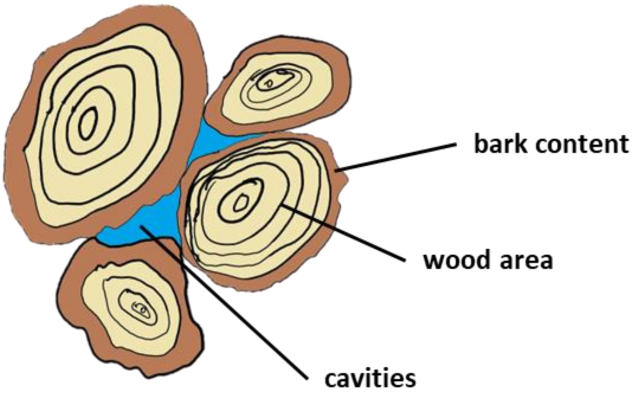
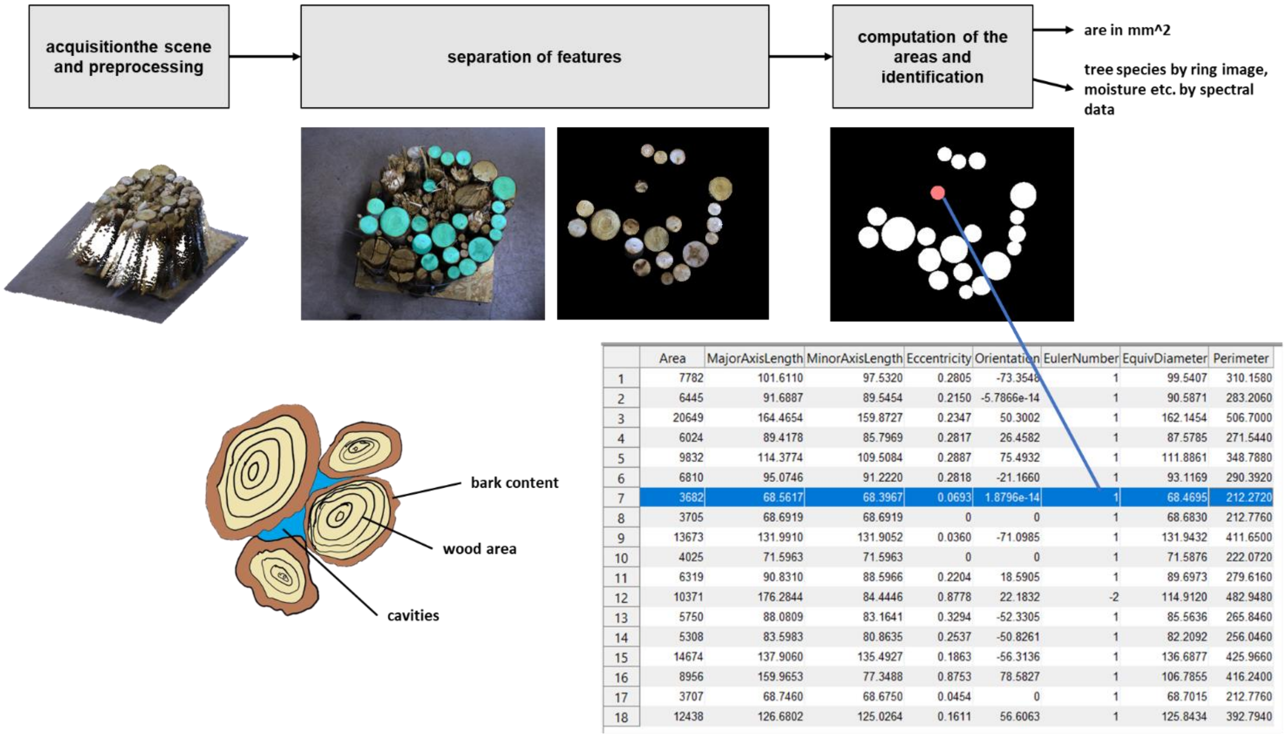


*Figure 7: Schematic measurement task.*

## 4.2 The methodology and algorithmic for direct acquisition on the aggregate

For the acquisition at the aggregate, it is assumed that the objects can be touched very close and the measurement results have a similar nature as the measurement results shown in Figure 4. The actual measurement task is shown schematically in Figure 7. One of the major problems is the separation of the end faces of the wood from the cavities. It is also interesting to determine the bark content. This would be possible in principle with additional spectral sensors but was not investigated in detail in this study. The qualitative assessment of the real measurement data (Figure 4) also allows the possibility to identify the ring pattern. For example, the age and the tree species could also be recorded.



|  | Area | MajorAxisLength | MinorAxisLength | Eccentricity | Orientation | EulerNumber | EquivDiameter | Perimeter |
|---|---|---|---|---|---|---|---|---|
| 1 | 7782 | 101.6110 | 97.5320 | 0.2805 | -73.3548 | 1 | 99.5407 | 310.1580 |
| 2 | 6445 | 91.6887 | 89.5454 | 0.2150 | -5.7866e-14 | 1 | 90.5871 | 283.2060 |
| 3 | 20649 | 164.4654 | 159.8727 | 0.2347 | 50.3002 | 1 | 162.1454 | 506.7000 |
| 4 | 6024 | 89.4178 | 85.7969 | 0.2817 | 26.4582 | 1 | 87.5785 | 271.5440 |
| 5 | 9832 | 114.3774 | 109.5084 | 0.2887 | 75.4932 | 1 | 111.8861 | 348.7880 |
| 6 | 6810 | 95.0746 | 91.2220 | 0.2818 | -21.1660 | 1 | 93.1169 | 290.3920 |
| 7 | 3682 | 68.5617 | 68.3967 | 0.0693 | 1.8796e-14 | 1 | 68.4695 | 212.2720 |
| 8 | 3705 | 68.6919 | 68.6919 | 0 | 0 | 1 | 68.6830 | 212.7760 |
| 9 | 13673 | 131.9910 | 131.9052 | 0.0360 | -71.0985 | 1 | 131.9432 | 411.6500 |
| 10 | 4025 | 71.5963 | 71.5963 | 0 | 0 | 1 | 71.5876 | 222.0720 |
| 11 | 6319 | 90.8310 | 88.5966 | 0.2204 | 18.5905 | 1 | 89.6973 | 279.6160 |
| 12 | 10371 | 176.2844 | 84.4446 | 0.8778 | 22.1832 | -2 | 114.9120 | 482.9480 |
| 13 | 5750 | 88.0809 | 83.1641 | 0.3294 | -52.3305 | 1 | 85.5636 | 265.8460 |
| 14 | 5308 | 83.5983 | 80.8635 | 0.2537 | -50.8261 | 1 | 82.2092 | 256.0460 |
| 15 | 14674 | 137.9060 | 135.4927 | 0.1863 | -56.3136 | 1 | 136.6877 | 425.9660 |
| 16 | 8956 | 159.9653 | 77.3488 | 0.8753 | 78.5827 | 1 | 106.7855 | 416.2400 |
| 17 | 3707 | 68.7460 | 68.6750 | 0.0454 | 0 | 1 | 68.7015 | 212.7760 |
| 18 | 12438 | 126.6802 | 125.0264 | 0.1611 | 56.6063 | 1 | 125.8434 | 392.7940 |

*Figure 8: Algorithmic flow chart for direct measurement and results.*

Figure 8 shows an example of the implemented algorithm for the determination of the wood face areas and its area as a flow chart. After the actual recording and a pre-processing, the separation of the features and then the calculation of the geometrical data is done. The output data of the tree species and the secondary parameters such as moisture etc., which can be calculated in principle, are given as an example. The multimodal data, consisting of 3D and color image information, are particularly useful for delineating the spaces. Thus, an algorithm was designed which takes both measurement variables into account and thus makes it possible to recognize the end faces as closed convex contours.

## 4.3 The methodology for indirect detection from a distance

With regard to the detection from a distance, two methods are conceivable in principle. The first solution would be to look at the harvested area and evaluate the negative (Figure 9 on the left). However, this variant is associated with further considerations that are clearly beyond the scope of this study. The second option is to probe the harvested bundle directly. (Figure 9 on the right). Although in this way, at most, only the half-hull of the wood bundle can be probed, there is also the possibility here to also gain information on the height of the entire bundle due to the possible perspectives. The trend in the investigations to the a priori information shows besides that the information to the height of the vegetation correlates likewise with the volume of the biomass. Thus, the methodology of probing on the aggregate was followed. The option presented in Section 2 of presenting the bundle to the measuring system at a defined point was rejected for the reason that this would result in too severe restrictions in the harvesting process and its economic efficiency.

*Figure 9: Practical setups for indirect measurement.*

In the next step, investigations were carried out directly on the machine. The aim here was to find a suitable perspective for the measuring technique. For this purpose, some well-defined tree trunks with a diameter of 20 cm were picked up with the aggregate as an example and the position of the measuring system was varied. Figure 11 shows the 4 selected perspectives, with the RGB color image and the colored point cloud shown in each case. It can be clearly seen that the perspective shown in the bottom right of Figure 11 provides the greatest information content. In addition, the observation was made here that a further measurement variable can be obtained from the information of the color image (Figure 10). In the point cloud registered with color data, it is possible to determine the opening angle of the aggregate's jaws.

*Figure 10: Detecting the opening angle of the jaw in high resolution RGB-image.*

The kinematics of the aggregate were reconstructed, which makes it possible to extrapolate the enclosed area of the jaws. Observations during an accompanied harvesting operation in practice showed that the compaction of the mass within this area is so high that almost no voids are created in this area. It can also be assumed that these compensate with the incoming compaction (squeezing) by the grabs. The opening angle of the gripper thus represents a validation variable, which is included in the calculation model. The area to be approximated directly above the gripper of the aggregate must therefore correspond in good approximation to the area enclosed by the grippers, which opens up a good possibility for cross-validation. Last but not least, optical probing has decisive advantages. It is not subject to wear due to the freedom from contact and can be applied to any aggregate. Only the kinematics must be known and the scenes calibrated.

*Figure 11: Evaluation of measurement perspectives for the indirect measurement.*

## 4.4 The algorithmic for indirect detection from a distance in detail

By the described measuring method the probing of a convex half-hull is possible. made possible. In addition, by registering the color data collected by the RGB cameras to the metric data in the point cloud, it is possible to detect and separate the foliage so that it does not act as an artificial enlargement of the actual volume. Deviating from the approach of extrapolating the biomass based on a precisely detected cross-sectional area, a possible approach here is to decompose the bundle of biomass into thin slices, which when integrated in the direction of height (z-dimension) will again yield the original point cloud. When the bundle is decomposed into thin slices, illustrative approaches to the calculation result. In the first step a compensation polynomial is developed in this 2-dimensional point cloud (Figure 12 left in red). By determining the start and end point, a curve section is created. If this curve section is now integrated in over the z-dimension, an area in space is created, which represents the "half hull" of the biomass. By mathematical methods the cross section can be extrapolated in each case on the basis of the probed "half hull". The exact mathematical procedure, taking into account all the findings, can be described as follows.

As already mentioned, it was observed in accompanied practical tests that the grippers of the aggregate compress the biomass very strongly. It can therefore be assumed to a very good approximation that immediately above the gripper the bundle of biomass can be regarded as a trunk. Consequently, the bundle of biomass can be described as growing along the height as if it were a growth with strong branching. This basic assumption makes it possible to scale the

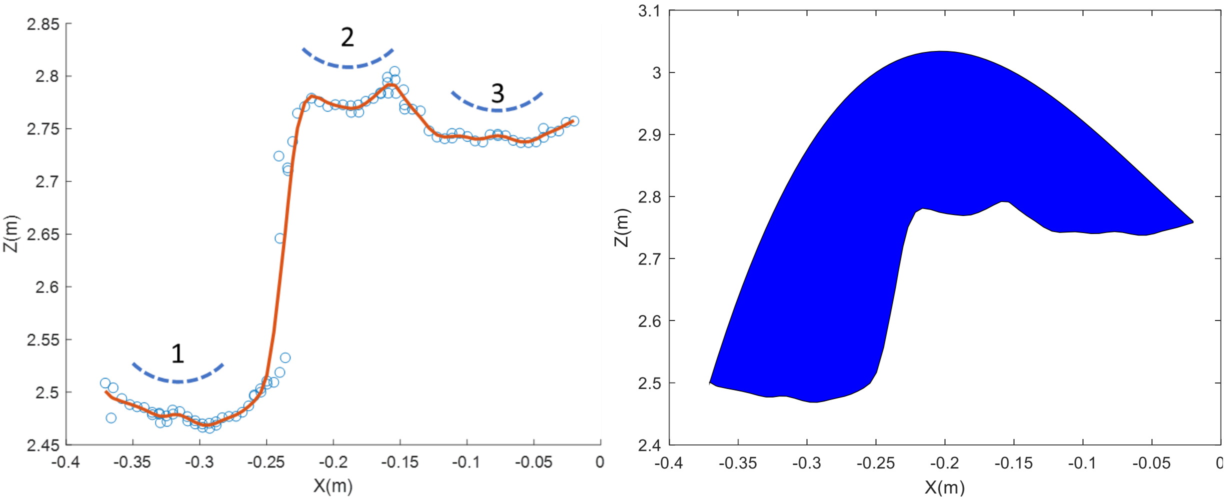


*Figure 12: Left: Calculation of the lower curve $l$ from the point cloud and counting convex shapes; Right: $l$ and approximated $l'$ with integrated area.*

relationships between stem diameter, height, and volume obtained empirically for weak woods for a larger diameter. A tree species-dependent correction factor vector $\underline{K}(B, h, n')$ was defined from the collected data. The vector addresses the empirical data and depends on the tree species B, the height h, and the "partial number" of branches $n'$. The number of branches is roughly counted in the detectable part of the frontal area by the algorithm (hence "partial number") and evaluated. The elements of the vector are a general correction factor $K_B$, a correction factor of the trunk diameter $K_{SD}$, of the specific bundle height influence $K_H$ and of the total height $K_{GH}$.

$$\underline{K}(B, h, n') = \begin{pmatrix} K_B \\ K_{SD} \\ K_H \\ K_{GH} \end{pmatrix} \qquad \textbf{(1)}$$

An analytical description of the volume to be approximated was made in the approach as follows. Initial condition for the approximation is an infinitesimally small volume section, which corresponds to the height of the discrete division of the volume along the height. This volume part is declared as initial volume $V_i$.

$$V_i = \int_0^{\tilde{h}_i} \left( \int_{x_0}^{x_1} l'(x)\, dx - \int_{x_0}^{x_1} l(x, \varphi_1, \varphi_2)\, dx \right) \cdot f_k(h)\, dh \qquad \textbf{(2)}$$

This initial volume is calculated from the difference of the curve $l$ actually probed by the measuring technique from the approximated curve $l'$ (Figure 12 right), which in turn is a function of the opening angles of the grippers $\varphi_1$ and $\varphi_2$. This difference describes the area between the beginning of the bundle $x_0$ and the end of the bundle $x_1$ directly above the aggregate. In addition, a correction function is weighted $f_k(h)$, which is a function of the discrete step size of the volume division $\tilde{h}_i$. This is not always expected to be constant and depends on the position of the relative coordinate system of the aggregate with respect to the reference coordinate system, since a tilted gripper theoretically affects the division and thus the accuracy. This was respected analytically here. For the approximated total volume $V_{ges}$, the approximated height volume $V_A$ is now added to the initial volume $V_i$.

$$V_{ges} = V_i + V_A = V_i + \int_{\tilde{h}_i}^{h} A_A\big(V_i, \underline{K}(B, h, n)\big) \cdot f_t\big(h, v(h)\big)\, dh \tag{3}$$

The approximated height volume results from integration of the approximated area $A_A$ over the height $h$, is again a function of the initial volume itself, the correction matrix $\underline{K}(B)$ and is weighted with a trend function $f_t\big(h, v(h)\big)$, which statistically describes a trend of the resulting expression of the mass bundle along the height. Arguments of this trend function are the height and a height-dependent history parameter $v(h)$, which describes the previous course of the real probed convex half-hull. The approximated area is enclosed by the extrapolated curve shape $l'$ and the real probed curve shape $l$, which can be described as a certain integral between the (height-varying) boundaries $x_{\min}(h)$ and $x_{\max}(h)$.

$$A_A = \int_{x_{\min}(h)}^{x_{max}(h)} l'(x, h, \underline{K}(B)\, dx - \int_{x_{\min}(h)}^{x_{\max}(h)} l(x, h)\, dx \tag{4}$$

In practice, further effects such as protruding twigs or branches are to be expected. These are then represented in the measurement data as isolated points. The characteristic feature is then a developing trend in the direction of the z-dimension, which can develop both upwards and downwards. Since the branch can develop both sagging and upwardly directed, no directional discrimination is possible here in the approach. However, it is decisive that the points with a trend develop either towards or away from the center of gravity of the point cloud. By these criteria it is now possible to separate individual branches or twigs. A rough count of the trunk elements is possible by evaluating the convex contours in the cross-section data (Figure 12 left). Isolated branches also correspond to this type of contour, only much smaller and with a (depending on the direction considered) "growing" distance to the center of gravity of the data. For an illustrative result, within a data set the real probed curve with an area of interest was limited to only one trunk. The empirical model lets the approximated curve $l$‘ change into an almost circular shape, which is why the integrated volume changes into the shape of a cylinder in a good approximation (Figure 13). The determined arc radius resulted in 0.0923 m, which corresponds approximately to the manually measured trunk diameter of 20 cm.

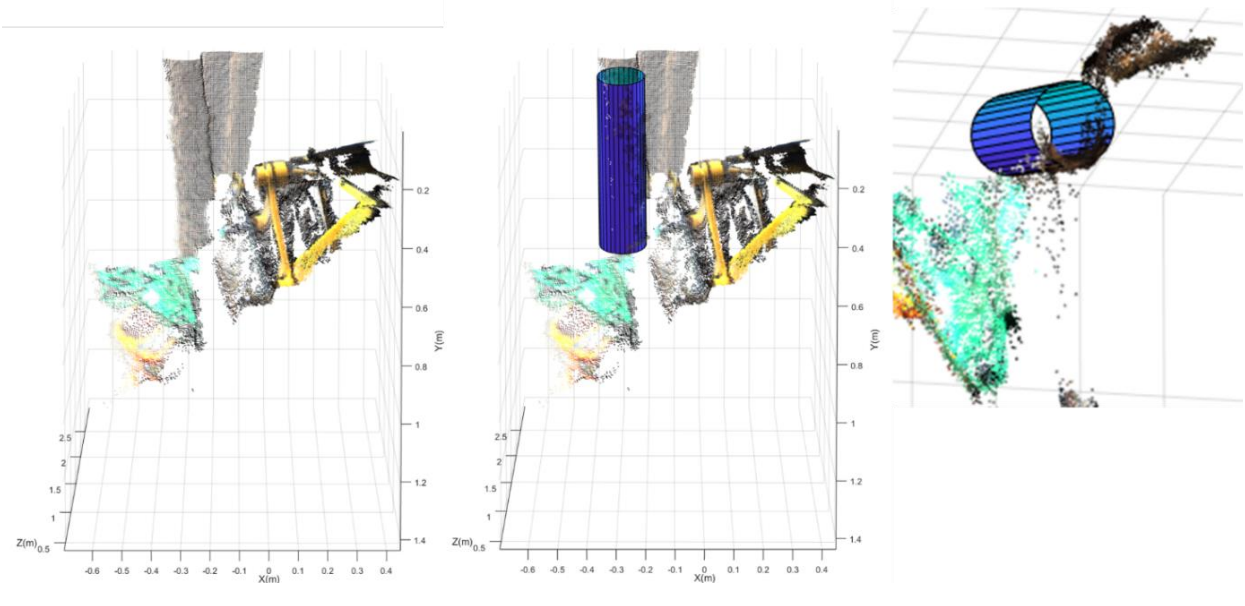


*Figure 13Exemplary result; Estimated biomass for one tree in the dataset.*

## 5. discussion of the solutions

Both solutions have proven their functionality. However, the method of direct probing on the aggregate has decisive disadvantages. On the one hand, this solution is tied to only one type of genset. Furthermore, extensive design changes and revisions to the aggregate itself are necessary in order to integrate the measuring system there. The possibility of also scanning the ring pattern offers a wider range of functions with regard to identification. The possibility of also touching the ring image, offers a wider range of functions regarding identification. In addition the accuracy is better, since no completely hidden part of the cross-section has to be of the cross section has to be approximated and also the examination of the a priori information results of the a priori information results (at least for hardwoods) in a significantly better correlation between the diameter or circumference and the volume as a target size. The methodology of indirect probing has significant advantages with respect to the system design. For example, the modularity is significantly better, which also allows retrofitting to any machine with any type of aggregate (assuming recalibration). In addition, the risk of contamination and generally the load on the measuring system due to the distance is lower. However, the system should be designed at least dual, so that an angle on the fret to be scanned is ensured, which increases the accuracy of the overall of the convex overall hull is significantly improved by a half envelope that is detected half hull is significantly improved. Depending on the type of machine, it makes sense here to have an arrangement of two 3D measuring systems with a base width of 1 m or more. One option is sketched in Figure 14.

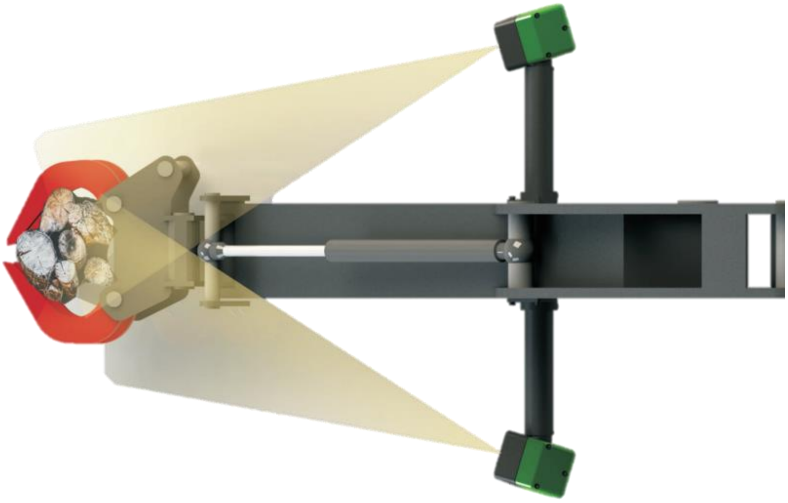


*Figure 14: Schematic dual system with 1m base width.*

## 6. Conclusion and further work

This paper describes methodologies for the optical determination of biomass using multimodal 3D sensing directly during the harvesting process. Two functional variants are explained and evaluated in terms of their advantages and disadvantages. Upcoming studies should address both the empirical correlation data and the extension of the system design. Further investigation of the correlations between parameters such as diameter, volume, age, and region in other tree species would give better a priori data. From a system engineering point of view, stabilizing the measurement through further measurement richness and, if necessary, the use of AI for measurement data stabilization makes sense. The inclusion of secondary characteristics (e.g., tree-specific spectral signatures for species identification) also offer enormous potential [5].

## 7. Acknowledgements

This project was funded by the „Thüringer Ministerium für Wirtschaft., Wissenschaft und Digitale Gesellschaft“ (TMWWDG). The work is related to the project “OBioM” (2019VF0009).

## REFERENCES

[1] F. Grundner and A. Schwappach, *Massentafeln zur Bestimmung des Holzgehaltes stehender Waldbäume und Waldbestände*. Leipzig, Frankfurt am Main: Deutsche Nationalbibliothek, 2022.
[2] R. Fütterer, M. Schellhorn, and M. Hänsel, *SoC-based real-time passive stereo image processing implementiation and optimization*: Ilmenau : Technische Universität, 2017, 2017.
[3] DAvid Deist, *Erhebung von Referenzdatensätzen zur empirischen Biomasse-Ermittlung von Laubbäumen in der Jungwuchsphase am Beispiel von Populus trichocarpa*. Bachelorthesis. Erfurt, 2022.
[4] Y. Dodge, *The Concise Encyclopedia of Statistics,* 1st ed. New York, NY: Springer New York, 2010.
[5] M. Richter, M. Rosenberger, J. Meister, R. Illmann, and G. Notni, *review of different multispectral indices for monitoring plant health in mid-mountain sites*: Bellingham, Wash. : SPIE, 1963, 2023.

## CONTACTS

M.Sc. Raik Illmann email: raik.illmann@tu-ilmenau.de
Dr.-Ing. Maik Rosenberer email: maik.rosenberger@tu-ilmenau.de
Prof. Erik Findeisen email: erik.findeisen@fh-erfurt.de