Preventive Detection of Human Tissue for a Safety Mechanism in Sawing Machines

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***Abstract*—Working with powered saws is generally considered to be one of the most dangerous jobs in terms of accidents per year. A large proportion of these accidents are characterised by the worker coming into contact with a running saw blade, often resulting in amputations and lifelong restrictions. To avoid this, especially for stationary saws active safety systems have recently come to the market. These systems react in a fraction of a second to a detected risk of injury and initiate a machine response that significantly reduces the likelihood of irreversible injuries, e.g. due to the saw blade sinking.**

The present work deals in particular with the sensor system for a band saw and aims at finding an optimal solution for the special conditions of this machine. After basic considerations, it becomes apparent that the long delays due to the circulating saw band and the often close working on the saw blade represent a major conflict. A speed-based concept is thought to avoid too deep restrictions here.

In the further course, a microwave-based concept is selected by means of an efficiency analysis. The applicability of this concept is examined using a test rig and a theoretical analysis. The approaches turn out to be not very promising. Further research is necessary to allow the intended use.

***Index Terms*—microwave, safety, woodworking, RADAR.**

I. BACKGROUND AND MOTIVATION

WORKING with powered saw blades has always been an inherently dangerous task. Be it the chain saw [[1]], the table saw [[2], [3]] or other, there exist plenty of examples. Often, injuries are caused by direct contact with the spinning saw blade. Since such contact easily results in amputations [4], a short moment of unawareness can result in a lifelong handicap of the affected person with noticeable loss in hand strength [5]. The continuously high number amongst professionals shows that even experience cannot fully mitigate the risk [5].

Due to a number of improved safety features and the growing awareness, this number has vastly decreased. But even today, injuries are still commonplace. As an example, the typical table saw is still responsible for around 28,000 emergency department visits [2], [6] and 2,000 finger amputations [7] per year in the US alone.

To finally overcome the issue, so called active injury mitigation (AIM) systems arise in recent past. Using various sensor technologies to detect a dangerous situation, these solutions bring the saw blade into a safe state, ideally before any irreversible injuries were inflicted. In the best case it may still at least reduce the effects of the accident.

A research in Occupational Safety and Health Administration (OSHA) investigation data reveals 5164 injuries for the search term *saw* from 1984 to February 2023 [8], with a band saw related share of 13.4 %. Thus the share related to band saw is notable and among the biggest overall. OSHA does only list occupational accidents within the US. If it is assumed that the percentage can be transferred to the worldwide accidents, the actual number would be substantially higher. This is especially true as there are more accidents in private than in an occupational environment [4]. A study of National Electronic Injury Surveillance System (NEISS) data speaks of 3000 to 4000 band saw injuries in total per year in

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woodworking alone [9].

Due to the danger, there exist already meat processing band saws with AIM technology. Examples are here [10] and [11]. However, these systems mainly focus on glove colour to detect the operator's hand and brake the blade in time. However, using gloves is generally avoided in woodworking and metal industries, as the necessarily more robust gloves can pull the entire hand with them, eventually worsening the injuries. Therefore the existing systems are rather limited. The objective of this work is to find and demonstrate an optimal sensor solution for an AIM system in a band saw that does not require gloves.

II. METHOD

A. Concept Development

To gain a basic understanding of the task, initially the ideal final result (IFR) is developed. The concept of the IFR originates from a widely used product development theory known as Theory of Inventive Problem Solving (TRIZ) and is for example described [12], [13]. The idea is to describe the ideal solution for a given problem without considering physical limits. Although being unrealistic, this helps to focus the development into the right direction. The ideal solution in this project is defined as a machine that would

> *exactly know when human tissue is about to touch the saw blade and trigger a stop just so much in advance that the following mechanisms can bring the machine into a non-harming state before irreversible injuries are inflicted.*

After further developing the fundamental theory, it is found that a major difference between an AIM system in a band saw compared to the existing systems in table saws is the increased delay. This is caused by the saw band, which cannot be retracted under the table as it is commonly conducted in virtually all table saw AIMs.

The solution to this is a speed-dependant approach. Using velocity as main parameter to trigger the safety reaction allows the best compromise of close working to the saw blade and still providing reasonable safety due to the expected delay.

Concepts are developed based on physical properties that allow differentiation between human tissue and the work piece. From the research in the state of the art and patents, some solutions are already known. The ideal solution is chosen using an efficiency analysis. During the process, each concept is assigned grades for the criteria. The criteria themselves stem from the basic functional concept developed before.

The analysis itself can be found in the thesis [14]. Eventually, a physical principle based on microwaves is chosen. In this concept, the volume around the saw blade is irradiated with microwaves. If a dielectric enters the monitored volume, a change of the transmitted signal is notable. As metal is highly conducting, this concept cannot be applied for these materials. However, for other materials such as plastics or wood it should be applicable due to the high water content in human tissue and the related high dielectric loss due to polarisation.

B. Concept Details and Background Theory

Basic knowledge for microwaves and the relevant technology can be found in [15]. Here, only the most important equations and findings are shown.

The distinction via microwaves is based primarily on the differences between the dielectric properties of human tissue and the work piece. The dielectric properties are described by the *conductance* σ, the *permeability* μ, and the *permittivity* ε. The differences for μ are neglected here, as only non-magnetic materials for the work piece are assumed.

μ and ε are also denoted as complex values, as they are usually frequency dependant. For human tissue, especially ε reduces drastically for the high frequencies given in microwaves. As an example, for blood the relative permittivity reduces from $\varepsilon_r(f = 1\,\mathrm{GHz}) = 45$ down to $\varepsilon_r(f = 100\,\mathrm{GHz}) = 8.3$ [16], [17]. However, the permittivity of human tissue is still notably higher than it is still higher than many thus enough for a basic identification.

The attenuation of electro-magnetic (EM) that occurs when it is sent onto a different dielectric is described in Eq. 1. It can be seen how the two characteristic wave parameters phase and amplitude depend on the distance travelled within the dielectric. The *attenuation coefficient* α displays the exponential attenuation of the wave amplitude due to dielectric losses inside the material, and the *phase coefficient* β shows the altered phase due to the material-dependant wave length. Both α and β depend directly on ω and therefore the frequency of the wave:

$$E(z,t) = T \cdot E_0 \cdot e^{-\alpha z} \cdot cos(\omega t - \beta z). \quad (1)$$

where

E_0 = electric field component of the EM wave

$\alpha = \omega\sqrt{\mu\varepsilon_r}\left[\frac{1}{2}\left(\sqrt{1+\tan^2\delta}-1\right)\right]^{\frac{1}{2}}$

$\beta = \omega\sqrt{\mu\varepsilon_r}\left[\frac{1}{2}\left(\sqrt{1+\tan^2\delta}+1\right)\right]^{\frac{1}{2}}$

z = the depth inside the dielectric

ω = the angular frequency of the electric field

T = the transmission coefficient.

Eq. 1 shows that the attenuation generally increases with rising frequency, and with higher permittivity ε and permeability μ. This is important for the choice of an exact frequency.

Reflection and transmission occur every time an EM wave hits the boundary of a different media. For transmission, this is taken into consideration from the *transmission coefficient* T. It is also purely dependant on the dielectric properties of the material. In short, the reflection is higher for a bigger difference between the two adjacent permittivities and vice versa.

To measure frequencies in the GHz-range, commonly mixer devices are used. In them, the signal of an oscillator $A\cos(x)$ is multiplied (mixed) with the signal received in the antenna $B\cos(y)$. Due to arithmetic relations, this results in so called intermediate frequency (IF), which is the sum and the difference of both signals at the mixer output:

$$A\cos(x)B\cos(y) = \frac{AB}{2}\left(\cos(x-y)+\cos(x+y)\right). \quad (2)$$

Since both signals are commonly close to each other, the difference is usually a very low frequency and the sum a very high one. This large difference allows to easily remove on of the two from the IF using a low- respectively high-pass filter.

Lastly, the power density PD_D of the radiation emitted from a non-isotropic antenna within a certain radial distance r is given by

$$PD_D = \frac{PG_r}{4\pi r^2}, \quad (3)$$

where

$P =$ average power of the transmitter

$G_r =$ antenna gain along boresight. Therefore, the power density falls of with the distance to the sender squared. All effects and some more have a major influence on a possible concept implementation. Therefore, some tests are conducted to see how big the effects actually are and how well they compare to the theory.

C. Experimental Setup

The physical principle is tested using existing radio detection and ranging (RADAR) chips which are based on microwaves. Two evaluation kits Infineon DEMO BGT60TR13C are used (see Fig. 1). These are fully integrated devices optimized for Industry 4.0 and general applications. Each device features three receiving antenna/device (RX) channels and a single transmitting antenna/device (TX) channel in a bandwidth from 58.0 GHz up to 63.5 GHz [18]. The received signal is fed through the analogue baseband chain consisting of a high pass filter, a low noise voltage gain amplifier and an anti-aliasing filter (AAF); parameters like cut-off frequencies and gains can be configured via Python. After this, the IF channels are sampled with on-chip 3-channel 12-bit analogue-to-digital converters (ADCs) with a maximum sampling rate of 4 MSps.

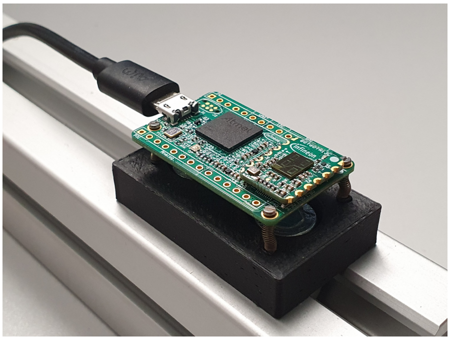

Fig. 1. Infineon microwave sensor on the 3D-printed mount.

Fig. 2. Test stand to evaluate the concept.

The Infineon baseboard is mounted on a 3D-printed socket designed to fit onto an aluminium profile. Three screws and springs of the socket allow angular adjustments during the test.

In the test rig made from aluminium profiles, two devices are mounted facing each other as shown in Fig. 2. A connection to the PC running Python is accomplished using a common USB2.0-connection. The test stand allows to measure the transmitted signal intensity. By bringing different obstacles and/or human tissue between the devices, adjusting the height, and much more effects like the dependence on different material thicknesses, shapes etc. can be visualized.

The devices report a float number for each measurement of the IF. This float number translates to the full scale (FS) value of the ADCs. Thus, a value of 1 means a full signal amplitude where the entire ADC range is used, and -1 to a recorded signal amplitude of zero. A frame consists of a set of measurements of the IF, here commonly 128 samples as shown in Fig. 3. In the figure, the difference due to the additional signal emitted from the second device is well received.

A Discrete Fourier Transform (DFT) is performed using the algorithm provided from the numpy package. The magnitude is shown in dB (FS), where a magnitude of 0 dB (FS) translates here now to a perfect sine-wave with an amplitude of exactly the ADC range. The resulting exemplary spectrum from the frames depicted in Fig. 3 are shown in Fig. 4. A distinct peak can be seen which represents the main signal frequency from the other device. Therefore, from this peak the magnitude and the respective frequency bin are taken. For the following results, commonly multiple frames are recorded and evaluated to get some statistic significance.

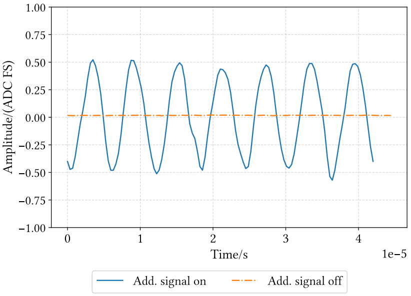

Fig. 3. Single frame raw IF data from one antenna.

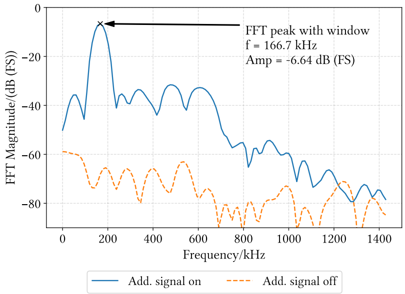

Fig. 4. Spectra of the raw IF frames from before.

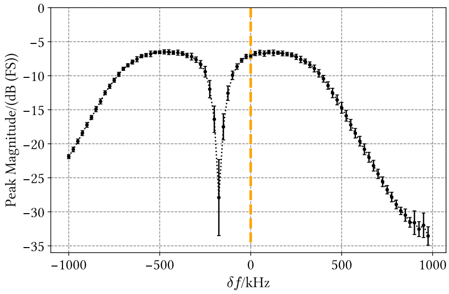

Fig. 5. Magnitude for a sweep across the frequency difference δf.

III. RESULTS

In a first test, it is shown how a frequency difference δf between the two devices is received. This measurement translates to Eq. 2. If both devices have the exact same frequency, the measured frequency in the IF should be at 0 Hz and thus a constant signal. As Direct Current (DC) is removed in the analogue measurement chain of the devices, this should also reduce the signal magnitude. Fig. 5 shows the result for 10 frames with standard deviation around the mean value depicted as error bars. The behaviour is expected, where the magnitude decreases for a certain δf and rises for higher and lower values. However, this occurs at a frequency difference of $\delta f = 160\,\text{kHz}$ and not for $\delta f = 0$. The best explanation is that there must be an unwanted offset between the set frequencies and the ones actually emitted from the devices. Judging from Fig. 5, setting $\delta f = 0$ results already in an almost optimal signal magnitude.

By looking a the frequency instead of the magnitude in Fig. 6, the explanation from before is confirmed. At $\delta f = 160\,\text{kHz}$, the frequency alternates around 0 Hz for the 10 frames recorded. It is also visible how the frequency peak varies drastically for higher values of δf. This is due to reduced signal amplitude, which leads to a less distinct peak and thus to the variations.

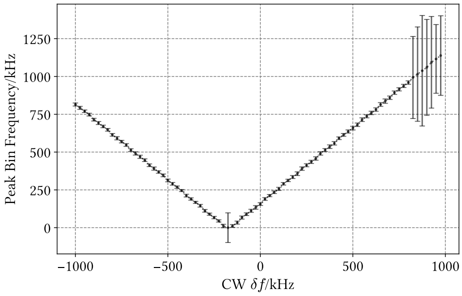

Fig. 6. Frequency for a sweep across the frequency difference δf.

In the next test, it is investigated how the distance between the two devices affects the signal transmission. A similar case would be given in the concept if the blade guard of the band saw is adjusted. In Fig. 7, it can be seen how the magnitude reduces with increasing distance (100 frames per setting). This can be related to Eq. 3 and thus a power function. Apart from the vertical offset (see y-axis on the right), both agree very good with a score of $R^2 = 0.95$. The offset is caused by the unknown absolute amplifications of antenna, anti-aliasing- and low-pass-filters etc. As the measurement agrees with the theory, this effect can be removed in the concept and does not represent a problem.

Additionally to the distance between the devices,

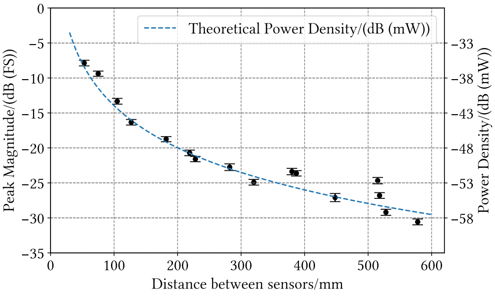

Fig. 7. Distance variation of the sensors.

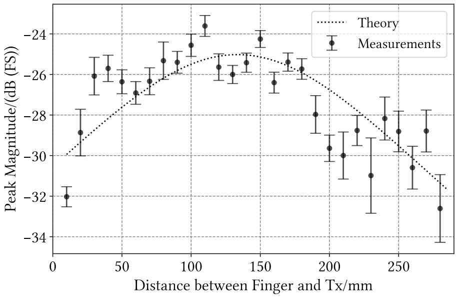

Fig. 8. Finger as obstacle in different distances.

also the distance to the obstacle may vary. This is tested by putting the finger exactly in boresight of the two devices, but in different heights. All other parameters are kept constant as before. The result can be seen in Fig. 8. The attenuation varies with the distance relative to the devices. The highest magnitude is received, if the finger is right in the middle between the two devices. A possible explanation is deflection and diffraction of the EM waves. For comparison, a parabola is plotted in the logarithmic plot, which reaches a score of $R^2 = 0.65$. The agreement is not perfect, but speaks for the theory. Also, increased variations are noticeable, which is due to the minimal movement of the finger.

Next is a measurement of the transmitted signal intensity through various types of wood. As can be seen in Fig. 9 the amplitude varies drastically depending on the material. Compared to that, the thickness seems to have a lower influence. This is also described in literature concerning the dielectric parameters of wood [19]. It can for example be seen that the MDF-MR board (MR= moisture resistant) has a very high attenuation despite its low thickness of $19\,\mathrm{mm}$. This is most likely due to the additions used to achieve the moisture resistance. Similarly, a spruce board with a thickness of $245\,\mathrm{mm}$ has a higher attenuation than a even thicker beech board, which is most likely due to the increased humidity in the wood. Overall, the variations make a differentiation between human tissue and other materials.

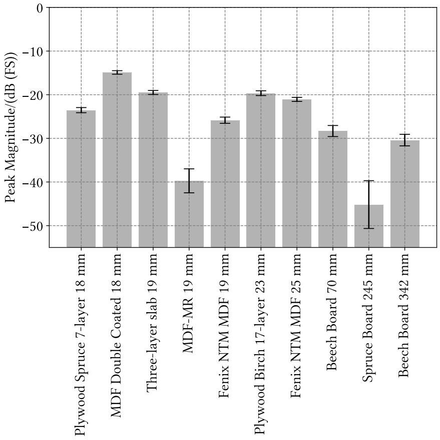

Fig. 9. Transmission results for different materials.

Eq. 1 forecasts an increasing attenuation with growing thickness of the dielectric. This effect might become problematic: additionally to the difficulties discovered before, a work piece with a very high thickness could result in equal attenuation as a thin finger. First, this is tested using a spruce board in various thicknesses. Fig. 10 shows the result for 100 measurements of each thickness, compared to a linear line as proposed in Eq. 1 (in a logarithmic plot). As can be seen, the agreement is reasonable. The

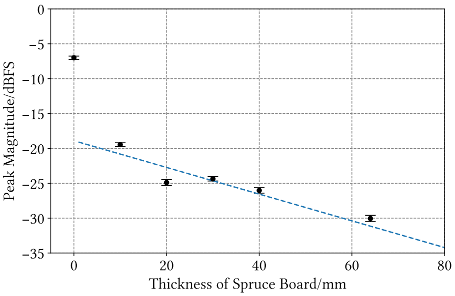

Fig. 10. Signal magnitude for various spruce thicknesses

deviations are most likely due to the uncertainties in the used devices together with the effects of the rather inhomogeneous material wood. While this result confirms the expectation, it also raises the assumption that a simple transmissive measurement is not enough for human tissue differentiation. However, since all these tests have been conducted with a EM wave frequency of 60 GHz, there is a chance that this is different for other frequencies.

Lastly, a measurement across the entire bandwidth of the device in 25 kHz steps is conducted. Due to resonances etc. it may be possible for the attenuation of the materials to be different for various frequencies. Here, a direct comparison of the transmissive signal magnitude of a thicker wooden board with the result for human tissue is conducted (here a human finger with a thickness of 16 mm and a human hand with 26 mm). For every test case, 10 measurements are conducted. The result is shown in Fig. 11. As can be seen, the set frequency does in fact make a major difference. While the attenuation of the spruce board is always higher than of the finger, this varies for the hand. Especially in the ranges around 59.5 GHz and 61 GHz, the signal magnitude after the hand is lower than after the almost ten times as thick spruce board. This may allow a differentiation, but needs further investigations.

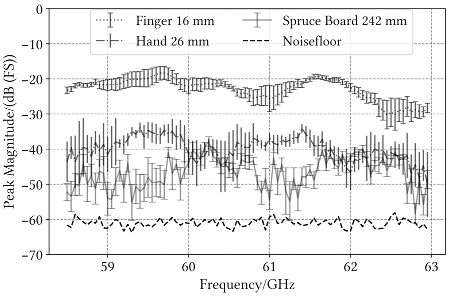

Fig. 11. Magnitude across the entire device spectrum.

IV. CONCLUSION

A. *Consequences of the work*

In this work a concept based on microwaves to allow preventive detection of human tissue in a band saw was developed and investigated. The concept is based on the different dielectric properties and thus not applicable for metal. However, for wood this should lead to differences in the attenuation of EM waves sent through either of the materials.

The tests conducted provided a detailed and practical look at the theory and the influences around microwave devices. Overall it was found that the applicability is much more difficult than expected. The used evaluation devices, due to recent developments rather cheap with $\sim$ 190€, are affected from significant uncertainties. Nonetheless, most of the basic theory could be confirmed with them. Overall, the concept needs further development, as with a simple transmissive measurement a differentiation is impossible.

Investigations of the entire spectrum surprisingly showed differences for some frequency bands. More detailed investigation of those areas may provide the necessary difference and allow the intended recognition.

B. *Limits of the approach*

The used low-power devices were not specifically designed for the application. While they allowed to gain basic results that can be translated to the general principle, custom designs especially of the antennas may improve the results. Effects due to the running machine such as vibrations or electric field of the used motor may play an additional role.

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