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Sensing Through Foliage

Lehvästön läpäisevät mittaukset

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CONTENTS

SUMMARY

This report is a part of Forestcluster Ltd's EffFibre research program. The aim of the program is to increase the availability of Finnish supply for raw wood materials and to enhance the cost-efficiency and competitiveness of the Finnish forest cluster. The technological and logistical solutions to boost up wood production are studied in part of the program.

The different technologies capable of seeing through foliage are examined and clarified in this report written with the Autonomous Systems research group, from the department of Automation and Systems Technology, Aalto University. Sensors seeing through foliage, bushes and other vegetation in the forest could enable better measurements and perceptions of trees, ground and obstacles for the operator of the forest harvester and for the autonomous, computer aided software helping the operator.

Modern sensor technologies and commercially available sensors including ultrasonic ranging, different radars and terahertz imaging devices are studied in this work. The search for different sensors is done focusing to the forest environment and its requirements. To measure trees and ground through foliage, the sensor has to be fast enough and the accuracy high enough to reliably detect tree trunks from other objects in the forest. In addition the surrounding environment should be observed omnidirectionally or at least with a large field of view of the sensor.

Ultrasonic rangers and sonars are the most cost efficient sensors presented in this work. They are mostly used for underwater sensing, but some in air sensors exist as well. The accuracy of ultrasonic sensors is not the best of presented technologies, but it might be accurate enough for sensing tree trunks, ground or large obstacles in forest environment. For more accurate sensing the work introduces short range millimeter wave radars. The most accurate radars can easily detect tree trunk sized objects. Radars have usually omnidirectional field of view and therefore they are suitable for sensing trees around the forest harvester.

The most accurate and newest sensor technology presented in this report is the terahertz imaging. These imagers operate in a similar fashion as lower frequency millimeter wave radars, but they take range images at terahertz frequencies. The theoretical accuracy is dependent on the measuring frequency and therefore terahertz sensors could be the most accurate sensors capable of observing through foliage. The terahertz imaging is usually used for scientific observations and in security industry to detect hidden weapons and explosives.

There is no ready made commercial sensor which would be suitable for measuring trees through foliage in forest, but the technological review shows that many of the presented technologies could be used to develop a sensor with required capabilities and accuracy to give the forest machine a view through foliage. Therefore new applied research should be focused to develop a new sensor to see through foliage with required accuracy.

TIIVISTELMÄ

Tämä raportti on tehty osana Metsäklusteri Oy:n EffFibre-tutkimusohjelmaa. Ohjelman tavoitteena on kasvattaa kotimaisen puuraaka-aineen saatavuutta ja parantaa puuntuotannon kustannustehokkuutta sekä koko klusterin kilpailukykyä. Osana ohjelmaa selvitetään tehostetun puuntuotannon vaatimia teknologisia ja logistisia ratkaisuja puunkorjuussa ja metsänhoidossa.

Tässä Aalto-yliopiston Automaatio- ja Systeemitekniikan laitoksen Autonomisten järjestelmien tutkimusryhmän EffFibre-tutkimusohjelmaan tekemässä raportissa selvitetään mahdollisia teknologioita, joilla voitaisiin nähdä tai havaita metsässä oksiston, lehvästön ja muun kasvillisuuden lävitse. Lehvästön läpi näkevät mittaukset mahdollistaisivat tarkemman puiden mittauksen ja havainnoinnin erityisesti runsaskasvustoisilla alueilla, kuten harvennuskohteilla. Näistä tarkoista mittauksista olisi hyötyä niin kuljettajan työssä kuin autonomisen metsätyökoneen kehityksessä.

Työssä selvitetään nykyaikaiseen ultraäänikaikuluotaukseen, tutkatekniikkaan, ja terahertsikameratekniikkaan liittyvää tutkimusta sekä saatavilla olevia antureita ja mittalaitteita. Olemassa olevaa tekniikkaa tarkastellaan metsässä tapahtuvaan mittaamiseen soveltuvuuden kannalta. Metsäkone ja metsän työympäristö asettavat omat vaatimuksensa mittalaitteelle, jonka tulee pystyä mittaamaan ympäristöä riittävän nopeasti ja riittävällä tarkkuudella. Lisäksi ympäristöä pitäisi pystyä havainnoimaan laaja-alaisesti monelta suunnalta metsäkoneen ympäriltä.

Työssä esitellyistä mittalaiteteknologioista ultraäänianturit ovat esitellyistä mittalaitteista edullisimmasta päästä. Niitä on yleisesti käytetty eniten vedenalaiseen havainnointiin, mutta myös ilmassa toimivia ratkaisuja löytyy. Niiden tarkkuus ei ole parhaimmasta päästä, mutta se saattaisi silti riittää puun tunnistamiseen muun kasvuston seasta. Tarkempina mittalaitteina työssä esitellään erilaisia lyhyen kantaman laajakaistaisia tutkia. Niistä tarkemmat pääsevät puun mittaamiseen tarvittavaan tarkkuuteen. Tutkat ovat yleisesti luonteeltaan joka suuntaan mittaavia, joten siksi ne olisivat erityisen hyviä metsäkoneen ympärillä olevien puiden havainnointiin.

Tarkimpana ja myös uusimpana mittalaiteteknologiana työssä esitellään terahertsikuvantamista. Terahertsialueen mittalaitteet toimivat normaaleja millimetrialueen tutkia huomattavasti korkeammilla taajuuksilla, joten niiden erottelukykykin on paljon korkeampi. Nykyisin tätä teknologiaa käytetään pääasiassa tarkkoihin tieteellisiin mittauksiin, sekä turvallisuusalalla ihmisten ja esineiden, kuten esimerkiksi matkatavaroiden läpivalaisuun.

Selvitystä tehtäessä ei onnistuttu löytämään yhtään valmista kaupallista mittalaitetta, jolla metsässä voisi havainnoida puita tai maanpintaa riittävällä tarkkuudella lehvästön ja kasvillisuuden lävitse. Sen sijaan jokaisen esitellyn teknologian, kaikuluotauksen, tutkatekniikan ja terahertsikuvantamisen alalta löytyy tieteellistä tutkimusta, jonka perusteella myös puiden havaitseminen lehvästön läpi olisi mahdollista. Soveltavaa tutkimusta tulisikin tehdä uusien metsäolosuhteisiin sopivien mittalaitteiden kehittämiseksi.

1 INTRODUCTION

A major problem for autonomous or semi-autonomous work in the forest is the discrimination between pliable and solid objects in the environment. The forest is full of vegetation, sprigs and leaves that can be safely passed through using the boom of the forest harvester. There are as well solid objects like tree trunks, branches, stones and the ground that should not be hit with the boom or with the tool at the end of it. Nowadays common sensors like laser scanners, or lidars, can only see nearest crossing object on the path of the laser beam emitted from the scanner. Similarly cameras can only see the nearest object in front of the objective. In the forest there are in most cases plenty of leaves and sprigs between the sensor and objects that are attempted to be observed.

Usage of laser scanners and cameras is complicated in complex environment, for example in the forest. The sensor observes a lot of noisy measurements between the sensor and target objects, like tree trunk or ground. These noisy measurements make the needed autonomous recognition of the ground, tree trunks and other objects challenging or in worst case nearly impossible. It would therefore be a great aid for any system that tries to cope in forest environment to use some sensor that can penetrate some foliage and leaves and sense larger solid objects inside foliage. An accurate sensor that sees trough foliage, sprigs and leaves could give a lot more usable information about the environment for the autonomous or semi-autonomous system that guides it through leaves and foliage.

2 SENSORS TO SEE THROUGH FOLIAGE

Many different sensor types are commonly used in nowadays robotic systems. Most common sensors types are cameras, ultrasonic sensors, laser scanners, and different kinds of radars. Cameras and laser scanners are not efficient to sense through dense foliage as explained above. Ultrasonic waves can in theory penetrate some leaves and sprigs, but in practice simple sonars just send a short pulse and give the echo from the nearest large enough object at the direction of the beam. Sonars used in robotics are usually transmitter receiver pairs with some beam directors or cones to narrow the sonar beam width. [1]

Some more complex sonar sensors are built for underwater usage. Especially side scan sonars, designed to sense underwater obstacles and seafloor, have narrow beam vertically to the direction of propagation. The sensor is mapping seafloor sideways as the sensor is pulled onwards [2]. Other way to get map of a seafloor is to have a rotating beam director in the sonar antenna to scan environment or to use synthetic aperture sonars [3]. Synthetic aperture means a system where the antenna is moved during scanning, and the resulting image is calculated from the multiple scans from different locations [4]. There are quite complex sonar sensors in medical use as well. There are many 3D and 2D sonar imaging devices to see inside human beings especially to see fetus inside womb [5].

Although sonar scanners or side scan sonars are widely used underwater and in medical imaging, they are not usually used in air medium. In air, ultrasound sensors are not as accurate as cameras or laser scanners. Therefore there has been only a little need for acoustic echoing and imaging sensors and only a few prototypes have been built [6]. Therefore there are no commercial sonar scanners or imagers to be used in air. Instead of commercial measurement devices which are capable of producing 2D or 3D map of the environment, there are simple ultrasonic rangers to measure distance. Some researchers have used multiple separate sonar rangers or rotated sonar using a servo motor to acquire distance data from different angles. These simple ultrasonic sensors, ultrasonic range finders have beam width of several degrees to tens of degrees and therefore angular resolution of the measurement is very low. [1] Separate sonars also disturb each other and can not be used simultaneously. Therefore the scanning time of self built system is slow. [7]

Instead of using sound waves, radio waves are more often used in air to acquire information about surrounding environment. Traditionally radars are used to detect ships or aircrafts or to detect rain or clouds in the sky. Those applications have usually a long range and low measurement resolution. These radars usually work by sending a short pulse to the antenna and waiting for the echo. The antenna is then rotated to get measurements from different directions. The radar technology is developed fast allowing it to be used at shorter ranges and giving more accurate measurements. Nowadays there are many kinds of radio detecting and ranging devices, pulse radars, Doppler-radars, continuous wave radars, frequency modulated radars, etc. [4]

Instead of sending a pulse and then waiting for the echo the frequency modulated continuous wave (FMCW) radar sends a continuous wave with a frequency modulated signal. The echo is received simultaneously as signal is sent. The distance is calculated as the difference of the frequencies of the sent and received signals. [8] Newest millimeter and submillimeter wavelength continuous wave radars have very high frequency from many gigahertzes to terahertz. These sensors are very accurate and can detect objects of a size of a few centimeters. These sensors are mainly built for military use or for security industry to see under clothes or through fog and smoke. [9]

Current sonar and radar sensor technology and current status of the research is presented in the next chapters.

2.1 Sonar sensors

Commercial ultrasonic sensors that are designed to work in air are usually simple pulse emitting devices that measure the time between emitted and received ultrasound sound pulse. This kind of commonly used sonar, SRF08 range finder, is shown in Figure 1 below. It has quite large beam width, 45 degrees. Because of the large beam width these sensors are not capable of separating different objects from each other; instead they are usually used as proximity sensors, to stop machines before collision. [10] Some researchers have used many simple ultrasonic sensors as a ring to map robots environment [11]. These sensors are also used in low cost and small robotics systems [12].

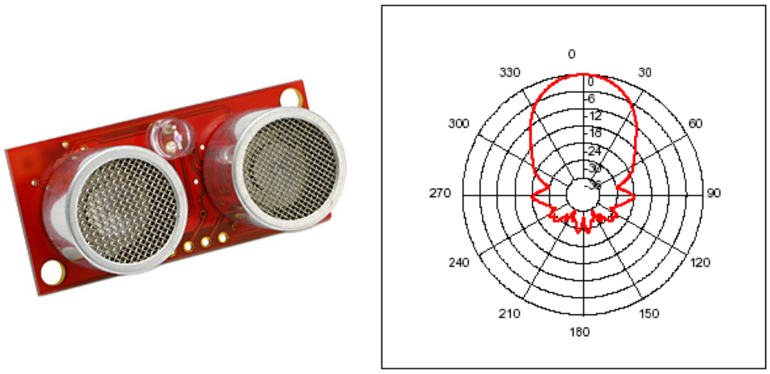

Figure 1: Simple sonar sensor, SRF08 Ultrasonic range finder on the left and its beam width on the right [10]

More accurate sonar sensors for air have beam width of around 5 degrees as can be seen in Figure 2 [14]. It is still much wider than a common laser scanner which has a beam width of less than one degree [13], and therefore accuracy that is acquired without complex calculation can not be as high as by using laser scanners and cameras instead of sonar sensors.

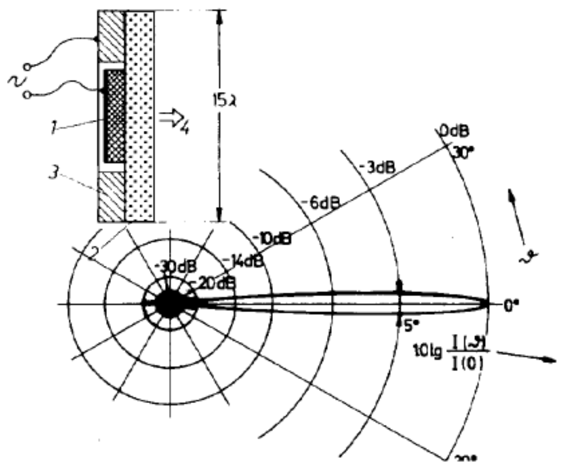

Figure 2: High directivity ultrasonic transducer: radiation pattern and design principle. 1) matching layer, 2) piezo-ceramic, 3) metal ring, 4) main lobe [14]

Synthetic aperture sonar (SAS) is a more complicated approach to mapping environment using ultrasound sensors [15]. It is a form of sonar in which sophisticated post-processing of sonar data are used in ways closely analogous to synthetic aperture radar. Synthetic aperture sonars combine a number of acoustic pings to form an image with much higher resolution than conventional sonars. The principle of synthetic aperture sonar is to move a sonar sensor along a line and illuminate the same spot on the sea floor with several pings. [15] There is some research done to build synthetic aperture sonars that work in air [6, 16], but commercial products are currently designed only for underwater use.

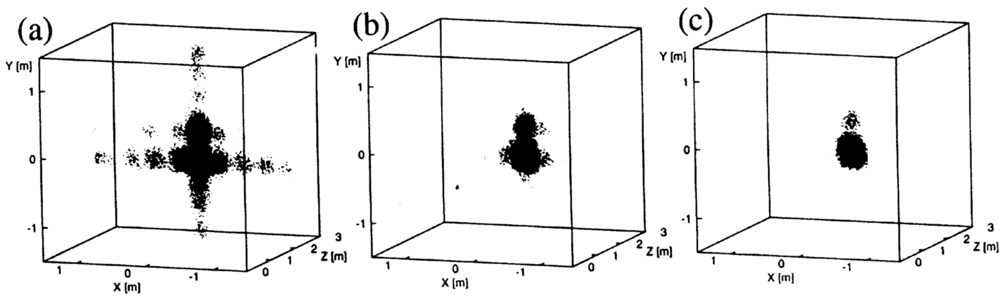

Figure 3: Acoustic images of a life-size human model target measured by the experimental synthetic aperture sonar system by Hiroshi Saruwatari and Mitsuo Komura [6]. Acoustic images a, b, and c are taken using different parameters.

Underwater sonar technology is more developed than the technology designed for air medium. Figure 4 presents Imagenex technology's version of sonar sensor developed to scan underwater targets. It has a lot more narrower beam and therefore it can scan underwater environment and get echoes from the bottom. This narrow beam width is easier to acquire under water, as the speed of sound on water is higher than on air. [3]

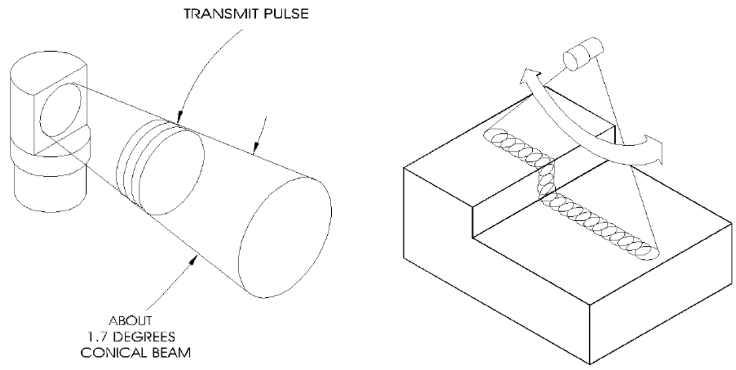

Figure 4: Imagenex rotating conical underwater sonar sensor on the left and the use of the sensor in the right [3]

Traditionally, most ultrasonic ranging systems are excited using pulse signals. Researchers at Tianjin University, China showed last year a new continuous way of measuring surroundings using sound waves. They proposed a method called chaotic sine frequency modulation (CSFM) sequence. A chaotic signal is excited to ultrasonic transducers and the echo is correlated with send data. Preliminary experiments show that the proposed CSFM sequences could meet the requirement of non-crosstalk ultrasonic ranging systems. [7] This method might make more accurate and faster ultrasonic rangers possible in air.

2.2 Radars

Conventionally used radars have usually long range and they are not suitable for robotic sensors where objects are near the robot and accuracy requirement is high. When the frequency of the radar is increased, its maximum spatial resolution increases as well. The high frequency and the need for very short pulse makes the use of conventional pulse radar complicated while operating on short ranges and while the depth resolution requirement is high. [4] Instead frequency modulated continuous wave (FMCW) radar can be used for short and very short ranges. For example Lissel et al. [17] showed 20 years ago that the FMCW radar is accurate enough to be used in car applications.

Newer research use FMCW radars to map robots environment as in the work by Checchin et al. [18] using K2Pi FMCW radar shown in Figure 5. The resolution of the K2Pi radar is only a few meters, but it can detect cars, trees and buildings. It is a traditional real aperture radar system that has one rotating antenna. Real aperture radar (RAR) is a device that first emits the signal and then collects the radiation. In a case where the antenna moves during measurement to produce synthetic aperture, the device is called synthetic aperture radar (SAR) [4].

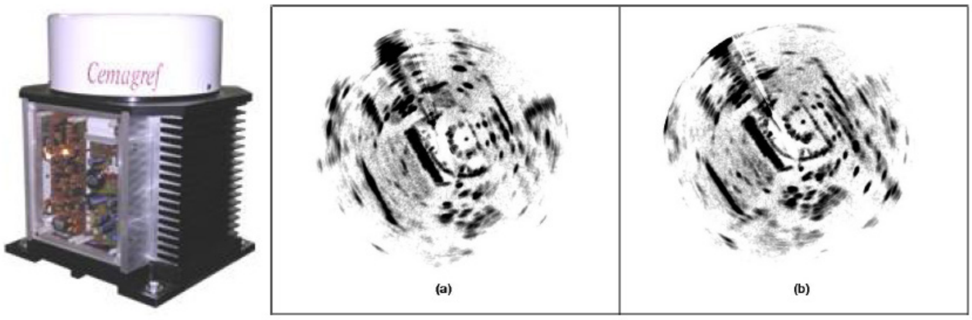

Figure 5: K2Pi FMCW radar for short ranges less than 100m at left, and its measurement data at right [18]

Even more accurate result can be acquired if the movement of the radar can be used in the calculation of the measurement. Usually airborne measurement devices are synthetic aperture devices that can scan environment while moving ahead. Michael Edrich presented a lightweight FMCW radar system, called MISAR, which operates at 35 GHz frequency [19]. It can make accurate measurement with a resolution of a less than a meter. The measurement device and resulting measurement from UAV is shown in Figure 6 below.

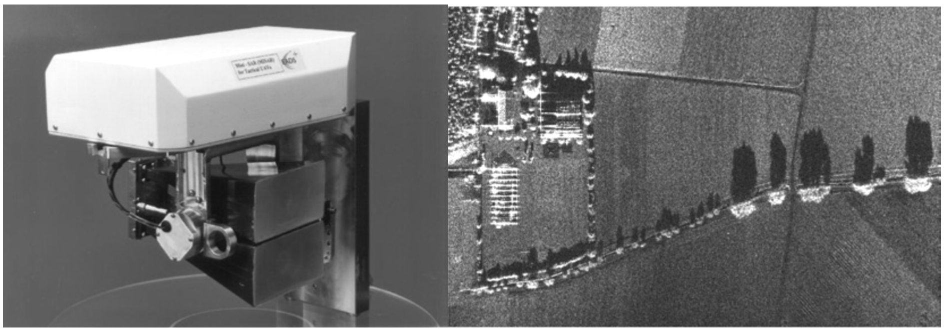

Figure 6: MISAR 35 GHz FMCW radar sensor and its measurement image from light weight UAV [19]

In military applications, as well as in our case, it is important to see through foliage. There are a few highly complex and accurate radars to see through foliage to detect tanks inside forest from above. For example the Jigsaw system is a foliage-penetrating 3D imaging laser radar system for military from air imaging [20]. The operational principle of the Jigsaw sensor and a drawing of a real sensor are shown in Figure 7. Figure 8 shows the capability of the Jigsaw sensor. The sensor is seeing through tree tops and leaves and while Marino et al. are visualizing different heights from the data, the tank is clearly shown in. The system is built to be mounted on a military helicopter. [20]

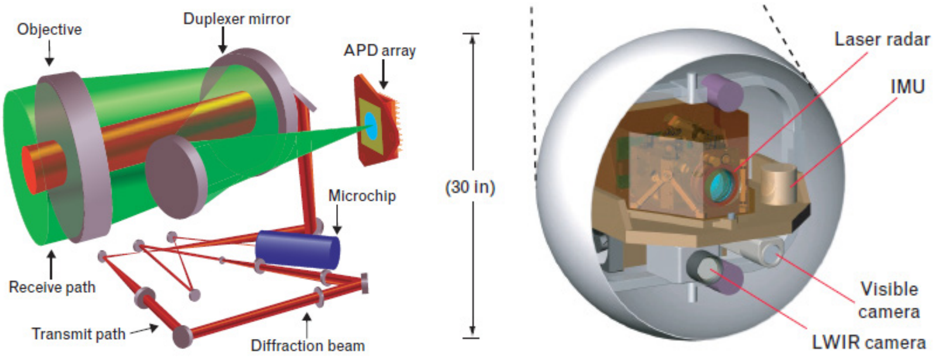

Figure 7: On the left an illustration of the transmit (red) and receive (green) optical paths in the Jigsaw sensor, on the right the Jigsaw sensor integrated into the 30-in diameter gimbal along with an inertial measurement unit (IMU), a visible camera, and a long-wave infrared (LWIR) camera. [20]

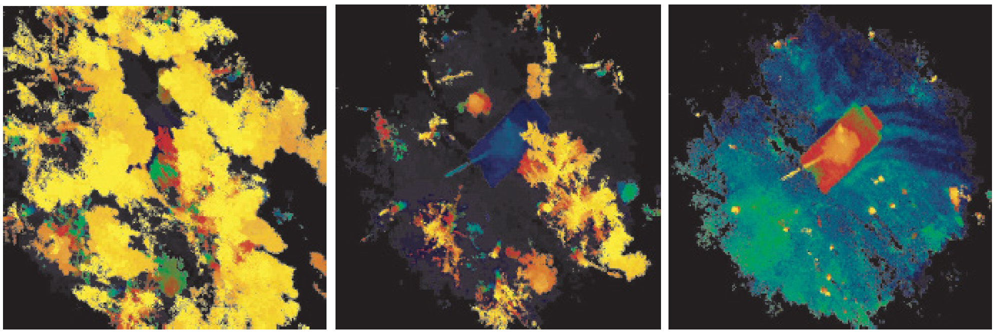

Figure 8: Visualization of the Jigsaw sensor measurement through foliage at different heights. The tank is clearly visible as only data reflected near ground is shown [20]

There are also less expensive radar devices that can acquire high resolution at short distances. For example Faiza Ali, Alexander Urban, and Martin Vossiek present a high resolution synthetic aperture 360° 2D imaging radar scanner. Their system is based on a FMCW radar unit and a small omnidirectional antenna that is mounted on a compact rotating platform. Figure 9 shows the operational principle of their SAR FMCW radar and Figure 10 shows the accuracy of the measurement in angular and spatial domain. This kind of radar can see through small obstacles as target is seen from multiple different directions and the resulting measurement is calculated from a set of separate raw measurements from different locations around the rotating disk. [21]

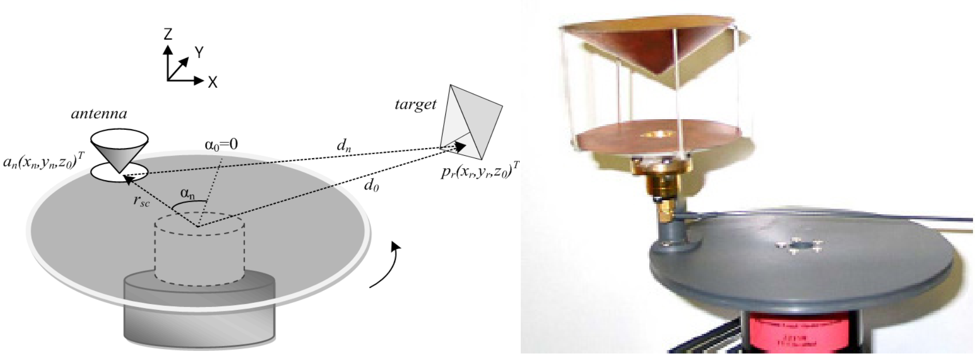

Figure 9: Principle and an image of the rotating FMCW radar antenna unit by Ali et al. [21]

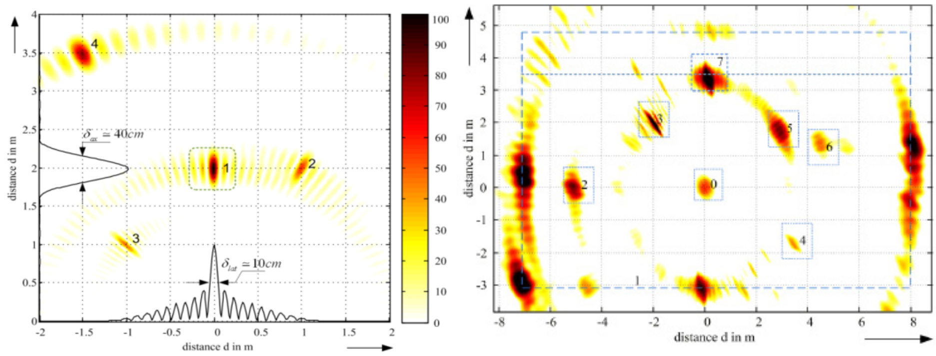

Figure 10: Measurement accuracy of the rotating FMCW radar scanner system by Ali et al. [21]

There is at least one low cost radar project to see through foliage. It is a robotic UWB-radar project by Brian Yamauchi from iRobot Corporation [22] aimed to make observations through foliage and grass. The project is named Daredevil and in it the robot is equipped with an ultra-wideband radar. They use Multispectral Solutions Radar Developers Kit Light shown in Figure 11, which uses 6 - 6.6 GHz frequency band and has 30 cm range resolution and communicates through USB. [22]

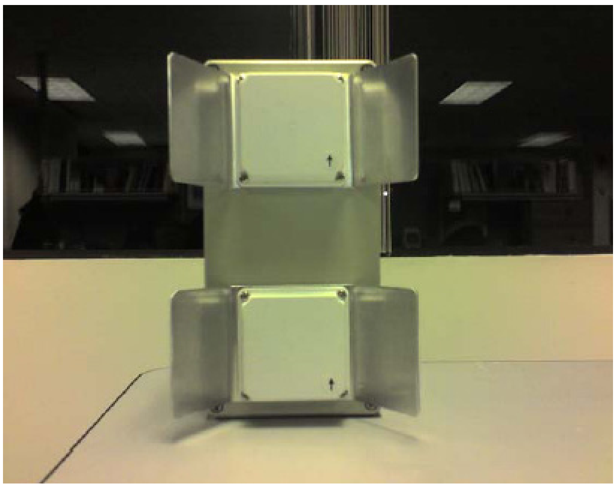

Figure 11: MSSI RaDeKL UWB radar used in the Daredevil project [22]

The system is not at all as accurate as previously presented state of the art measurement devices, but this one uses commercial radar system. Yamauchi shows that UWB can effectively penetrate sparse foliage (such as deciduous bushes without leaves) but not very dense foliage (such as evergreen bushes with leaves). He reports that they can see a solid wall through foliage. They are planning to study next how they can discriminate between solid objects and echoes from the foliage. [22]

2.3 Terahertz imaging and submillimeter-wave radars

Newest millimeter and submillimeter wavelength continuous wave radars have very high frequency from many gigahertzes to terahertz. These sensors work in a similar manner as radars, but the frequencies are extremely high. They are mainly built for military use or for security industry to see under clothes or through fog and smoke. [9]

Cooper et al. showed in their study that a high-resolution imaging radar operating at 576–605 GHz is capable of detecting weapons concealed by clothing while scanning from ranges of 4–25 m. Their system is able to image a torso with 1 cm resolution at 4 m range in about five minutes. Figure 12 shows a reflector and a lens system and the principle of the operation. [9] It is very similar to Jigsaw laser radar presented previously [20]. Figure 13 shows the capability of the high resolution imaging radar as the concealed weapon is detected through shirt [9]. Cooper et al have also explained how the Terahertz transmitter and scanning system works in their other paper [23].

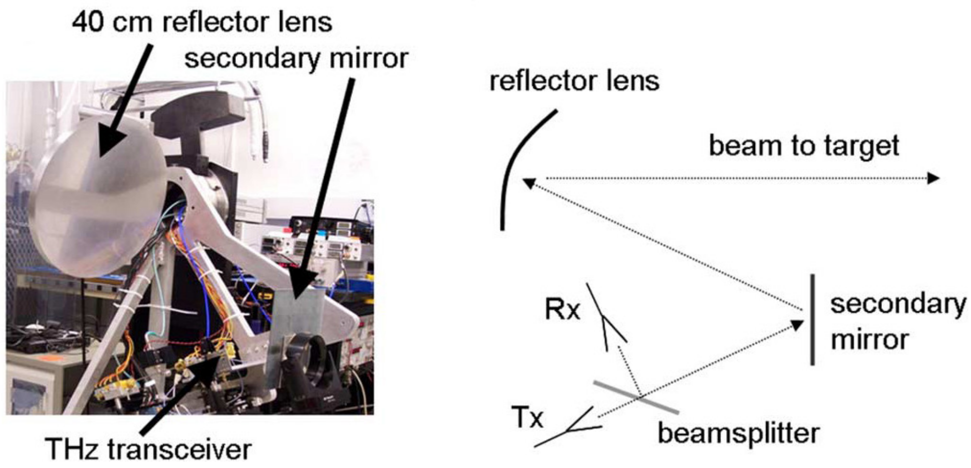

Figure 12: A 600 GHz radar photograph at left and optics schematic at right [9]

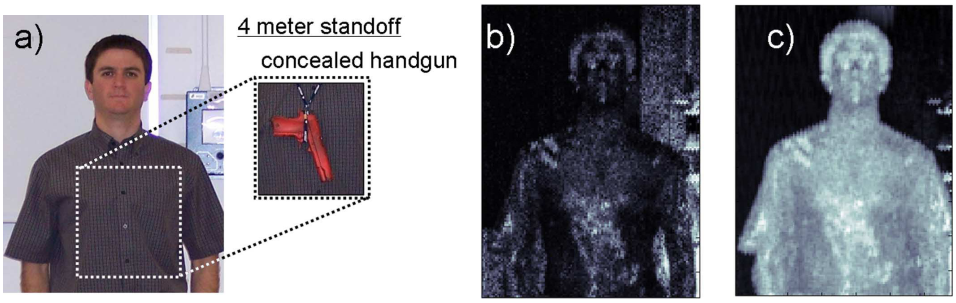

Figure 13: High-resolution imaging radar operating at 576–605 GHz is capable of recognizing concealed weapon under shirt [9]

Terahertz imaging is an accurate measuring technology used in many areas other than security industry, where the accurate information about the inside of the object is needed without breaking the target. Ayesha Younus gives a detailed presentation about terahertz imaging and its usage for investigating artworks and for computer tomographic imaging in her doctoral thesis [24]. According to her work, the accuracy of the technology is in artwork cases less than a micrometer, and in tomography cases depending from the used technology from a few millimeters to a centimeter [24]. The accuracy of terahertz imaging would be at least sufficient to see trees through foliage.

3 CONCLUSION

Through foliage observing capability can be achieved using either sound or radio waves. Sonar technology is developed mainly for observing underwater obstacles and objects, but it could be used in air also as Saruwatari and Komura showed [6]. Most sensor technologies that are able to see through foliage are FMCW radars operating on gigahertz or terahertz frequencies as presented previously. They can form very accurate 3D image of the environment. Gigahertz radars were able to detect obstacles smaller than one meter, up to approximately 10cm resolution [21], and terahertz devices were able to measure at least to 1cm resolution [9], and in high detail artwork research cases up to a few micrometers [24].

Only drawback is that the most accurate radar systems are US military equipment [20] or scientific research tools, and they are probably very expensive measuring devices. Some UWB radars are commercial [22], but most of the high accurate radars are research tools made in the universities or in collaboration with corporations and are not for sale. As presented in this work, it is possible to develop a sensor that sees through foliage at least by either using sonic echoing, millimeter wave radar, or by terahertz imaging.

A ready made commercial sensor system suitable for measuring trees through foliage in forest was not found in this work. Although the study of the different sensing technologies shows that many of the presented technologies could be used to develop a sensor with required capabilities and accuracy to give the forest machine a view through foliage. Therefore new applied research should be done to develop a new sensor to see through foliage with required accuracy.

4 REFERENCES

[1] T. Tanzawa, N. Kiyohiro, S. Kotani and H. Mori, "The ultrasonic range finder for outdoor mobile robots," *in Intelligent Robots and Systems 95. 'Human Robot Interaction and Cooperative Robots', Proceedings. 1995 IEEE/RSJ International Conference on,* 1995.

[2] P. Åkesson, "Side Scan Sonar," [Online], Internet: http://www.abc.se/~pa/mar/sidescan.htm, 1999, [Jan. 15, 2012].

[3] Imagenex Technology Corp., "Sonar Theory and Applications," [Online], Internet: http://www.imagenex.com/sonar_theory.pdf, 2001, [Jan. 15, 2012].

[4] M. I. Skolnik, "Radar Handbook," McGraw-Hill, 2007.

[5] G. Sakas, "Trends in medical imaging: from 2D to 3D," *in Computers Graphics*, 2002.

[6] H. Saruwatari and M. Komura, "Synthetic aperture sonar in air medium using a nonlinear sidelobe canceler," *in Electronics and Communications in Japan (Part III: Fundamental Electronic Science)*, 1999.

[7] Yu-Long Song, Q. Meng, Jiao-Jiao Zhang and M. Zeng, "Non-crosstalk ultrasonic ranging system excited using chaotic sine frequency modulated sequences," *in Image Analysis and Signal Processing (IASP), 2011 International Conference on,* 2011.

[8] A. G. Stove, "Linear FMCW radar techniques," *in Radar and Signal Processing, IEE Proceedings F*, 1992.

[9] K. B. Cooper, R. J. Dengler, N. Llombart, T. Bryllert, G. Chattopadhyay, E. Schlecht, J. Gill, C. Lee, A. Skalare, I. Mehdi and P. H. Siegel, "Penetrating 3-D Imaging at 4- and 25-m Range Using a Submillimeter-Wave Radar," *Microwave Theory and Techniques, IEEE Transactions on*, 2008.

[10] Devantech Ltd, SRF08 ultra sonic range finder. [Online], Internet: http://www.robot-electronics.co.uk/htm/srf08tech.shtml, [Jan. 15, 2012].

[11] Xiuqing Wang, Zengguang Hou, Yongqian Zhang, Min Tan, Anmin Zou and Hongming Wang, "Scene analysis for mobile robot based on multi-sonar-ranger data," *in Information Acquisition, 2006 IEEE International Conference on,* 2006.

[12] Huan Dinh and T. Inanc, "Low cost mobile robotics experiment with camera and sonar sensors," *in American Control Conference, 2009. ACC '09.* 2009.

[13] SICK, Sensor Intelligence, Laser measurement sensors. [Online], Internet: http://mysick.com/, 2008, [Jan. 15, 2012].

[14] V. Magori, "Ultrasonic sensors in air," *in Ultrasonics Symposium, 1994.Proceedings., 1994 IEEE,* 1994.

[15] R. E. Hansen, "Introduction to Synthetic Aperture Sonar," 2011.

[16] P. K. Mukhopadhyay, A. J. Wilkinson and M. R. Inggs, "Synthetic aperture sonar 3-D imaging of targets in air using multiple, non-parallel shot lines," *in Geoscience and Remote Sensing Symposium, 2005. IGARSS '05. Proceedings. 2005 IEEE International,* 2005.

[17] E. Lissel, H. Rohling and W. Plagge, "Radar sensor for car applications," *in Vehicular Technology Conference, 1994 IEEE 44th,* 1994.

[18] P. Checchin, F. Gérossier, C. Blanc, R. Chapuis and L. Trassoudaine, "Radar Scan Matching SLAM Using the Fourier-Mellin Transform," 2010.

[19] M. Edrich, "Ultra-lightweight synthetic aperture radar based on a 35 GHz FMCW sensor concept and online raw data transmission," *in Radar, Sonar and Navigation, IEE Proceedings*, 2006.

[20] R. M. Marino, "Jigsaw: a foliage-penetrating 3D imaging laser radar system," *The Lincoln Laboratory Journal*, 2005.

[21] F. Ali, A. Urban and M. Vossiek, "A high resolution 2D omnidirectional synthetic aperture radar scanner at K band," *in Radar Conference (EuRAD), 2010 European,* 2010.

[22] B. Yamauchi, "Daredevil: ultra-wideband radar sensing for small UGVs," *in Proceedings of SPIE--the International Society for Optical Engineering*, 2007.

[23] K. B. Cooper, "A high-resolution imaging radar at 580 GHz," *In IEEE Microwave and Wireless Components Letters*, 2008.

[24] A. Younus, "Imagerie Térahertz 2D et 3D: Application pour l'étude des matériaux du patrimoine culturel," *Doctor's thesis, University of Bordeaux*, 2011.