

## 論文の内容の要旨

論文題目 Study on Performance Improvement of Amplitude-Modulated Continuous-Wave Laser Scanner  
(振幅変調連続光レーザスキャナの性能向上に関する研究)

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With the rise of Industry 4.0, smart factory is fast becoming a key concept in infrastructures. To realize the autonomous production system, it is necessary to ensure the parts are properly manufactured. 3D scanners are expected to play a vital role in quality assessment in smart factories. The objects to be measured in factories can be small components such as gear wheels, or they might be large volume parts such as the bodies of cars. Therefore, both high precision and measurement distance of several meters are required. Moreover, there has been a movement in the construction industry to replace conventional dimensional measurement and maintenance of buildings and building materials with remote automatic measurement. For example, it is applied to tunnel shape inspection and crack inspection. The amount of shape displacement caused by concrete cracks is typically approximately 200  $\mu\text{m}$ . To realize automation such as an autonomous production system and inspection of architectural structures *etc.*, a high-definition and highly reliable 3D measurement instrument that can be applied to a variety of situations is required.

With looking at the research and development of conventional 3D scanners, there is a trade-off relationship between the distance resolution and the measurement distance. For example, a typical time-of-flight laser scanner has a measuring distance of over 100 m, but has a range resolution of several cm. It can be used for autonomous driving and collision avoidance in automobiles and robotics, however, cannot measure the detailed characteristics of an object. On the other hand, a method using light interference can

realize a distance resolution on the order of nm, but the measurement distance is limited to cm order. This thesis summarizes the research and development on a 3D laser scanner with both improved longitudinal resolution and measurement distance. The amplitude-modulated continuous light (AMCW) 3D laser scanner developed in this research has a measuring distance of 5 m and a distance resolution of about 19.2  $\mu\text{m}$ . In order to realize such specifications, there are a number of problems to be coped with. In this thesis, I proposed solutions to these problems and took measures. These problems are ranging uncertainty, data degradation and data loss, and limited horizontal/vertical resolution. Regarding ranging uncertainty, treatment was performed by dual-modulation frequencies and data processing. Subsequently, speckles occur due to the interaction between the coherent light and the surface of the object having roughness, and the reception power may be extremely reduced to incur data deterioration. Data loss then occurs due to the limited dynamic range of the receiver of the laser scanner. Regarding the former, I focused on the polarization dependence of speckles, and alleviated such an impairment by speckle reduction employing a newly proposed high-speed polarization scrambling method. The latter was solved by properly mounting a low-noise optical amplifier, a pellicle beamsplitter, and a polarization-independent high-speed variable optical attenuator using electro-optic ceramics in the receiver. Next, laser scanners generally employ collimated laser beam, and the beam diameter at the exit of the scanner is on the order of cm to mm. Therefore, it is difficult to evaluate detailed characteristics of the object surface. We proposed two solutions to this problem. The first is the introduction of a focusing optical system. The beam diameter at the focal point is 100  $\mu\text{m}$  or less, and the focal depth is around several cm. Distortion of the 3D point clouds in the out-of-focus region was handled by data processing. The second proposal is to introduce a Bessel beam. We succeeded in generating a Bessel beam with m-class propagation distance by a proposed beamforming configuration, and we performed ranging by combining this beamforming with AMCW method.

The above-mentioned research results are expected to contribute to high-precision 3D measurement in Industry 4.0. For example, high-precision shape inspection of complex parts, shape inspection of engine assembly parts which requires  $\mu\text{m}$ -order resolution, shape inspection of soft and delicate objects, reverse engineering, identification of the reasons of defective parts, removal of rejection of non-defective parts, 3D scanning for digital archives of cultural assets, design in prostheses.

Finally, during the above-described 3D measurement on industrial products or the like having a surface roughness, I found that the materials can be classified from the polarization dependence of speckle. The physics behind this is subsurface scattering. In addition, the fact that materials such as industrial products having surface roughness can be classified by utilizing the polarization of light, which has not recognized in conventional 3D shape measurement, is an academically important discovery.