Dual Mode Optical Measurement Sensor for 3D Surface Reconstruction and Crack Detection

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Abstract. A dual mode optical measurement sensor was developed to measure free form surfaces and detects cracks revealed with liquid penetrant test. The fusion of a multi-line laser triangulation sensor with texture images, acquired by the sensor, allows the detection of the crack and the calculation of position and orientation for proper positioning and alignment of a friction stir welding head for crack repair. In order to test the proposed procedure, the sensor was mounted on a motorized linear stage to measure a simulated crack on a pipe section. Results show that the crack can be detected and the 3D position and orientation can be defined on the reconstructed surface for crack repair procedures.

1. Introduction
The great applicability of three-dimensional (3D) reconstruction makes it a highly researched, important and promising field. Optical measuring techniques have advantages compared to conventional mechanical techniques. The lack of contact, the speed in measuring a large number of points and measurement uncertainties that can be compared to contact systems are very attractive advantages in choosing an optical measurement method [1]. Laser triangulation sensors (LTS) are commonly used in non-contact dimensional metrology. These sensors are able to obtain 3D coordinates from projection of known geometric patterns on the surface of interest. They basically consist of a camera and a laser emitter properly positioned. By combining information from the intersection of the laser light on the surface to be measured with the perspective projection matrix of the camera, obtained during sensor calibration, it is possible to reconstruct the 3D coordinate corresponding to the 2D point in the camera image [2][3].

Due to an existing demand for solutions in the assembly of components under intense stress in the construction of offshore structures, a closed chain robot with a friction stir welding head was developed [3][4] and with it came the necessity of a vision system for inspection of free form surfaces and detection of cracks revealed with liquid penetrant inspection. Furthermore, the vision system was designed to assure proper positioning and alignment of the friction stir welding head for crack repair. Figure 1 shows the closed chain robot with the stir welding head and optical sensor installed.

2. Dual Mode Measurement Sensor
The LTS seen in Figure 2 and detailed in the Figure 3, was developed to attend to a specific application. Its design allows the topology measurement of the surface of interest without the need of removing the sensor for the realization of repairs by welding. The optical configuration was set to a
maximum sensitivity of 50 mm in Z, using a camera with resolution of 1280 x 960 pixels and a 12 mm focal length lens; 3 laser lines length of approximately 100 mm; vertical distance 180 mm from the sensor to the surface and Z measurement uncertainty in the order of ± 0.1 mm.

**Figure 1.** Closed chain robot with the stir welding head and optical sensor installed.

**Figure 2.** Optical sensor installed in the central hub of the robot, pointing toward tool coordinate system.

The projection of three laser lines allows to measure more points per acquisition and, from a single positioning and acquisition of the sensor, the position and orientation of the surface can be known. In the dual mode of the sensor, the laser lines can be programatically shut off and LEDs shut on to acquired images from the surface texture. Both images are used in the developed process to measure the crack trajectory in the 3D free form surface.

![Sensor configuration mounted on a part similar to the robot central hub.](image)

**Figure 3.** Sensor configuration mounted on a part similar to the robot central hub.

The mathematical modelling of an LTS is made to describe the relation between the position of the plane of light in pixel in the image and the corresponding position in mm in space. The parameters of the mathematical model can be determined through a calibration. The LTS mathematical model and its calibration were based on [5][6][7]. The measurement model uses the pinhole camera model (equation 1) and a fitted mathematical plane (equation 2) for each projected laser light plane. Therefore, for an acquired image it is possible to determine the 3D point \( \mathbf{M} = (X, Y, Z, 1)^T \) corresponding to the point \( \mathbf{m} = (u \cdot w, v \cdot w, w)^T \) in the image. There is only one 3D point which belongs to the line joining \( \mathbf{m} \) to the projection center and the fitted mathematical plane, simultaneously (equation 3).
Besides the point cloud measurement for 3D reconstruction, the sensor also allows to acquire texture images in order to detect signalized cracks. The developed crack 3D trajectory measurement using this dual characteristic and the projection of three laser lines simultaneously, which permits knowing the position and orientation of the surface with only one acquisition, are the main contribution of this work.

3. Creating Mesh from Point Cloud Measurement and Detecting Crack from Texture

Before starting the measurement procedure, the surface must be prepared so as to highlight discontinuities not visible to the naked eye, such as cracks, pores and folds. The liquid penetrant test, for example, is a simple way to highlight these surface faults.

In order to test the proposed measurement procedure, the sensor was mounted on a motorized linear stage (MLS) for scanning and the programmed translation is considered in the point cloud calculation. The surface of interest has a simulated crack. The setup can be seen in Figure 4. For each positioning of the system two images are acquired as seen in Figure 5.

From the point cloud measurement, the mesh is generated using the Delaunay triangulation method. The texture images are processed in order to detect and segment the crack. Once the crack is detected in the LED image, its 3D position is defined from points that are coincident with the detected laser lines, so can be signalised on the point cloud as belonging to the highlighted crack. Nevertheless, due to the crack width, the center of the crack is defined as the mean point. The point cloud representing the surface (white), the 3D position of the crack (red) and the detected center of the crack (yellow) are shown on figure 6.
The vision system’s goal is to assure proper positioning and alignment of a friction stir welding head to perform repairs by inserting pins along the crack. In order to set the 3D positions and orientation for pin insertion, a predetermined step is defined and the 3D positions are calculated over the crack by accumulating the distances between crack center 3D points until the desired step. Once the positions for pin insertion are known, the surface normal vectors are calculated for each point. This is done by taking 3D points in the neighbourhood (e.g. radius of 3 mm) of the positions for pin insertion and adjusting a plane to each point set. The reconstructed surface model with signalized crack, the positions for pin insertion and the corresponding normal to the surface (yellow arrows) can be seen on Figure 7.

**Figure 6.** Point cloud of the surface (white), crack (red) and crack center (yellow).

**Figure 7.** Surface with points and normal direction for crack repair procedure.

4. Conclusions
This work presents a dual mode measurement sensor and its integration to a motorized linear stage for scanning. The vision system is able to detect crack in free form surfaces and define the position and orientation for pin insertion along the crack. A reconstructed model of the surface is presented applying the Delaunay triangulation method to the point cloud. Future work includes sensor integration to a six degrees of freedom robot for crack detection and following. The system developed will allow inspecting the surface to be welded, detect cracks, and position the tool to perform repairs through automatic robot movement.

5. References
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