ROTOR STABILITY

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Abstract Recovering the three dimensional structure of a scene accurately and robustly is important for object modelling and robotic grasp planning, which in turn are essential prerequisites for grasping unknown objects in a cluttered environment. Shape recovery techniques are broadly described as either passive or active. Passive methods include recovering shape from a single image using cues such as shading, texture or focus, and shape from multiple views using stereopsis or structure-from-motion. Passive shape recovery has relatively low power requirements, is non-destructive and more akin to our biological sensing modalities. However, the accuracy and reliability of passive techniques is critically dependent on the presence of sufficient image fea tures and the absence of distractions such as reflections .

Keywords Transport, Optimization, Mechanics

1. Conventional Light Stripe Ranging and Related Work

Light stripe ranging is an active, triangulation-based technique for non-contact surface measurement that has been studied for several decades . A review of conventional light stripe scanning and related range sensing methods . Range sensing is an important component of many robotic applications, and light stripe ranging has been applied to a variety of robotic tasks including navigation , obstacle detection , object recognition for grasping and visual servoing.

Figure 1 illustrates the operation of a conventional single-camera light stripe sensor. The principle is similar to binocular stereo with one of the cameras replaced by a light plane projector (typically a laser with a suitable lens). The stripe reflected from the target is measured by the camera and each point in the 3D surface profile (for example X in Figure 1) is reconstructed by triangula- tion, using the known transformation between the camera and projector.

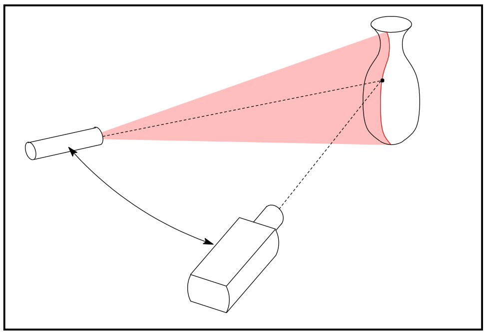

Fig.1. Conventional single-camera light stripe sensor

To capture a complete range image, the light plane is mechanically panned across the target and the range slices are registered into a mesh.

The drawback of conventional single-camera light stripe ranging is that favourable lighting conditions and surface reflectance properties are required so the stripe can be identified as the brightest feature in the image. In practice, this is achieved by coating the target with a matte finish, using high contrast cameras or reducing the level of ambient light. When the range sensor is intended for use by a service robot to recognize unknown objects in a domestic or office environment , various noise mechanisms may interfere to defeat stripe detection: smooth surfaces cause secondary reflections, edges and textures may have a stripe-like appearance, and cross-talk can arise when multiple robots scan the same environment.

A number of techniques for improving the robustness of light stripe scanners have been proposed in other work, using both stereo and single-camera configurations. Magee *et* develop a scanner for industrial inspection using stereo measurements of a single stripe. Spurious reflections are eliminated by combining stereo fields via a minimum intensity operation. This technique depends heavily on user intervention and *a priori* knowledge of the scanned target. Trucco *et al.* Use stereo cameras to measure a laser stripe, and treat the system as two in- dependent single-camera sensors. Robustness is achieved by imposing a number of consistency checks to validate the range data, the most significant of which requires independent single-camera reconstructions to agree within a threshold distance. An- other constraint requires valid scan-lines to contain only a single stripe candidate, but a method for error recovery in the case of multiple candidates is not proposed. Thus, secondary reflections cause both the true and noisy measurements to be rejected.

Nakano *et* develop a similar method to reject false data by requiring consensus between independent scanners, but using two laser stripes and only a single camera. In addition to robust ranging, this configuration provides direct measure- ment of the surface normal. The disadvantage of this approach is that each image only recovers a single range point at the intersection of the two stripes, resulting in a significant acquisition delay for the complete image.

Other robust scanning techniques have been proposed using single-camera, single-stripe configurations. Nygards and Wernersson identify specular reflections by moving the scanner relative to the scene and analyzing the motion of recon- structed range data. Periodic intensity modulation distinguishes the stripe from random noise. Both of these methods require data to be associated between multiple images, which is prone to error. Furthermore, intensity modulation does not disambiguate secondary reflections, which vary in unison with the true stripe. Alter natively, Clark *et al.* Use linearly polarized light to reject secondary reflections from metallic surfaces, based on the observation that polarized light changes phase with each specular reflection. However, the complicated acquisition process requires multiple measurements through different polarizing filters.

Unlike the above robust techniques, the method described below uniformly rejects interference due to secondary reflections, cross-talk, background features and other noise mechanisms. A significant improvement over previous techniques for error detection is a mechanism for the *recovery* of valid measurements from a set of noisy candidates. The reconstructed depth data is optimal with respect to sensor noise, unlike the stereo techniques , and stereo measurements are fused with the light plane parameters to provide greater precision than a single-camera configuration. Finally, conventional techniques using a special camera for stripe detec- tion typically require a second camera to measure colour. The ability to operate in ambient indoor light allows our sensor to measure implicitly registered colour and range in the same camera.

2 Robust Stereoscopic Light Stripe Sensing

As discussed above, the shortcomings of light stripe sensors arise from the difficulty in disambiguating the primary reflection of the stripe from secondary reflections, cross-talk and other sources of noise. The following sections detail the principles of an optimal strategy to resolve this ambiguity and robustly identify the true stripe by exploiting the redundancy in stereo measurements.

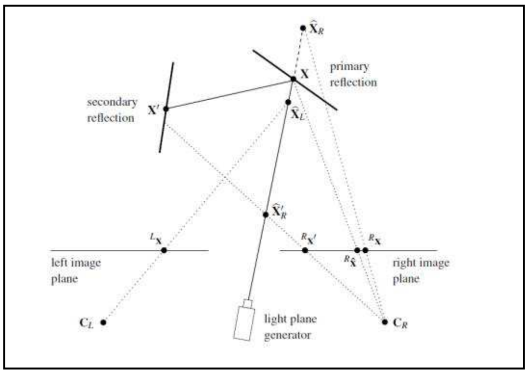

Fig.2. Validation/reconstruction problem

A primary reflection at X that is measured (using a noisy process) at *L* x and *R* x on the stereo image planes. However, a secondary specular reflection causes another stripe to appear at X , which is measured on the right image plane at *R* x but obscured from the left camera (in practice, such noisy measurements are produced by a variety of mechanisms other than secondary reflections). The 3D reconstructions, labelled X*L* , X*R* and X*R* in Figure 2, are recovered as the intersection of the light plane and the rays back-projected through the image plane measurements. These points will be referred to as the *single-camera reconstructions*. As a result of noise on the CCD (exaggerated in this example), the back-projected rays do not intersect the physical reflections at X and X .

The robust scanning problem may now be stated as follows: given the laser plane position and the measurements *L* x, *R* x and *R* x , one of the left/right candidate pairs, (*L* x,*R* x) or (*L* x,*R* x), must be chosen as representing stereo measurements of the primary reflection. Alternatively, all candidates may be rejected. This task is referred to as the *validation problem*, and a successful solution in this example should identify (*L* x,*R* x) as the valid measurements. The measurements should then be combined to estimate the position of the ideal projection *R* xˆ (arbitrarily chosen to be on the right image plane) of the actual point X on the surface of the target.

Formulation of optimal validation/ reconstruction algorithms should take account of measurement noise, which is not correctly modelled in previous related work. Laser stripe measurements are validated by applying a *fixed* thresh- old to the difference between corresponding single-camera reconstructions (X*L* , X*R*

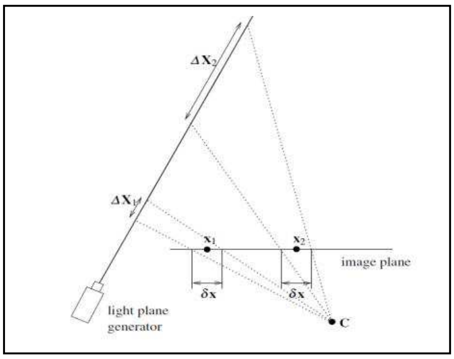

Fig.3. Variation of reconstruction error with depth

and X*R* in Figure 3). Such a comparison requires a uniform reconstruction error over all depths, which Figure 3.3 illustrates is clearly not the case. Two independent measurements at x1 and x2 generally exhibit a constant error variance on the image plane, as indicated by the interval δ x. However, projecting δ x onto the laser plane reveals that the reconstruction error increases with depth, since Δ X1 < Δ X2 in Figure 3. Thus, the validation threshold on depth difference should increase with depth to account for measurement noise, otherwise validation is more lenient for closer re- constructions. Similarly, taking either X*L* , X*R* or the arithmetic average 1 (X*L* + X*R*) as the final reconstruction in Figure 2 is generally sub-optimal for noisy measurements.

The following sections present optimal solutions to the validation/reconstruction problem, based on an error model with the following features (the assumptions of the error model are corroborated with experimental results :

1. Light stripe measurement errors are independent and Gaussian distributed with uniform variance over the entire image plane.

2. The dominant error in the light plane position is the angular error about the axis of rotation as the plane is scanned across the target, which couples all measurements in a given image.

3. All other parameters of the sensor (described in the following section), are assumed to be known with sufficient accuracy that any uncertainty can be ignored for the purpose of validation and reconstruction.

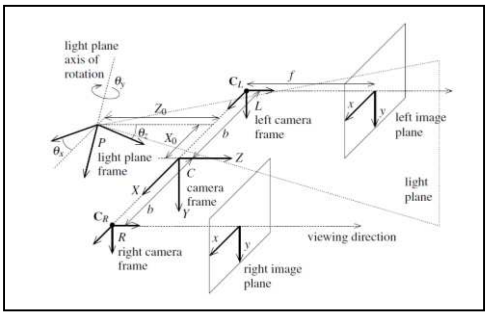

Fig.4. Light stripe camera system model

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