Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 48-9 (2015) 239–244

# Autonomous Collision Avoidance for Rendezvous and Docking in Space Using Photonic Mixer Devices

**Julian Scharnagl** * **Lakshminarasimhan Srinivasan** *
**Karthik Ravandoor** * **Klaus Schilling** *

* *University of Würzburg, Chair of Computer Sciene VII, Germany,*
*(e-mail: {scharnagl | srinivasan | ravandoor | schi}*
*@informatik.uni-wuerzburg.de)*

**Abstract:** An autonomous collision avoidance system that is based on a Photonic Mixer Device camera is presented. It is specially designed for close range maneuvers in space, like rendezvous and docking and on-orbit servicing. The 3D imaging sensor provides relative position and orientation information of an observed target in close vicinity. Pose estimation, trajectory prediction and collision detection are performed on-line and serve as input to the collision avoidance system. In the event of an imminent collision, the required velocity corrections ($\Delta V$) to perform a collision avoidance maneuver are calculated. Different trigger criteria like a cone-shaped approach corridor and a velocity profile are taken into account. $\Delta V$ computation is based on Hill-Clohessy-Wiltshire equations with the targeted hold point on V-bar as parameter. The system has been implemented in a complete framework including camera-based pose estimation and collision detection. Hardware-in-the-loop tests have been performed in a setup consisting of two industrial manipulators equipped with a Photonic Mixer Device camera and a satellite mockup model.

*Keywords:* Collision avoidance, collision detection, motion estimation, spacecraft autonomy, satellite applications, rendezvous and docking, on-orbit servicing

## 1. INTRODUCTION

The field of proximity operations in space is continuously evolving. Technologies and approaches for close range maneuver of cooperating spacecraft like docking to the International Space Station (ISS) by transporters such as the Russian Progress, the European Automated Transfer Vehicle (ATV) or the private SpaceX Dragon are well established and commonly used. Proximity operations to non-cooperative spacecraft like Rendezvous and Docking (RvD) to damaged, tumbling satellites or On-Orbit Servicing (OOS) tasks like refueling or Active Debris Removal (ADR) are gaining importance during the last years and thus are a continuously growing field of research (Sellmaier et al. (2010)). Since motion and state of non-cooperative spacecraft can neither be controlled nor exactly determined in advance, new technologies with a higher amount of autonomy are required. Experimental missions already have been undertaken (e.g. DARPA Orbital Express mission (2007) or NASA Robotic Refueling Mission (RRM) (2013)) and are planned (e.g. DARPA Phoenix).

Advances presented in this paper have been developed in the scope of the DLR "Forschungsverbund Robotische On-Orbit Servicing Technologien" (FORROST) project, a precursor to the originally planned DLR "Deutsche Orbitale Servicing Mission" (DEOS) mission (cf. Reintsema et al. (2010)). FORROST aimed at developing new technologies for autonomous OOS maneuvers with non-cooperative spacecraft. In this scope University of Würzburg has developed a complete framework consisting of a 3D visual sensor (Photonic Mixer Device (PMD)), pose estimation, collision detection and collision avoidance. In this paper the collision avoidance system is presented that completes the whole framework and adds important safety features for proximity operations in space.

## 2. PROJECT SETUP

The collision avoidance system that will be described in this paper has been developed as part of a larger close range navigation framework, although it is not limited to be used in it. It completes the framework consisting of PMD 3D sensor, pose estimation algorithm, trajectory prediction and collision detection software. These different parts of the project setup are detailed in this chapter.

### *2.1 Photonic Mixer Device*

PMDs are a special type of 3D cameras using Time-of-Flight (ToF) principle. Cameras consist of the actual PMD sensor and active illumination unit(s). The illumination units emit modulated Infra Red (IR) pulses of light to illuminate a scene, while the sensor measures the phase shift between the back-scattered light and a reference signal. Thus the distance to an observed object can be detected (cf. Hussmann et al. (2008)). This process is implemented on a pixel base, so range information is perceived for each pixel and no post-processing is required (typical resolution: 204 x 204 pixel cf. PMDTechnologies (2011)). PMD sensors are relatively small (typical sensor size: 12 x 12 mm$^2$

2405-8963 © 2015, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2015.08.090

Fig. 1. PMD[Vision] ® CamCube 2.0 camera with two infrared illumination units.

cf. PMDTechnologies (2014)) and are available at a fraction of the price of currently used systems in space like Light Detection And Ranging (LIDAR), though providing high frame rates (typical value: 25 fps cf. PMDTechnologies (2011)). A major drawback of PMD sensors is the maximum measurable unambiguous range of a few meter (typical value: 7.5 m cf. PMDTechnologies (2011)), but it has recently been shown that this can be extended using multiple modulation frequencies (typical value: 75 m (theoretical) and 22 m (experimentally proven) cf. Tzschichholz & Schilling (2013)).Fig. 1 shows the PMD sensor that has been used in this setup, namely the PMD[Vision] ® CamCube 2.0 manufactured by PMDTechnologies GmbH. Due to its characteristics PMD sensors show interesting potential in space applications complementing common vision-based relative navigation sensors like CCD cameras. Since PMD sensors have not been used in space yet, emphasis is on showing their readiness and benefits for space applications.

### *2.2 Pose Estimation*

A pose estimation algorithm has been developed that gathers the 3D information provided by a PMD camera. 3D images are analyzed using edge detection techniques to determine the faces of the main body of an observed target satellite. Subsequently the relative distance and orientation of the detected main surface and thus the target satellite with respect to the camera coordinate frame is computed. The algorithm is able to provide up to 10 data sets per second. More details on the pose estimation algorithm are given in Tzschichholz et al. (2011), Regoli et al. (2012) and Regoli et al. (2013).

### *2.3 Trajectory Prediction*

Based on relative pose information the future relative trajectory of a satellite in close range to another satellite is predicted using Hill's equations together with the according solution by Clohessy & Wiltshire (1960) (Hill-Clohessy-Wiltshire (HCW) equations). The Hill's equations describe the relative motion of a follower spacecraft with respect to a leader on a nearly circular orbit in close range (up to few km). In homogeneous form (without disturbing and/or control accelerations) they are defined as

$$\ddot{x} - 2\,n\,\dot{y} - 3\,n^2\,x = 0 \tag{1}$$

$$\ddot{y} + 2\,n\,\dot{x} = 0 \tag{2}$$

$$\ddot{z} + n^2\,z = 0 \tag{3}$$

where the x-axis is along the radius vector, the z-axis along angular momentum vector and the y-axis completes the right handed system (Local Vertical/Local Horizontal (LVLH) or Hills coordinate frame). $n = \sqrt{\mu/a^3}$, where $\mu$ is the Earth's standard gravitational parameter and $a$ the semi-major axis of the leader's orbit. The Hill's equations have been solved analytically by Clohessy & Wiltshire (1960) presenting the following solution (from Alfriend (2010)):

$$\begin{aligned} x(t) = &+ [4\;x_0 + \frac{2\;\dot{y}_0}{n}] + \frac{\dot{x}_0}{n}\;\sin(n\;t) \\ &- [3\;x_0 + \frac{2\;\dot{y}_0}{n}]\;\cos(n\;t) \end{aligned} \tag{4}$$

$$\begin{aligned} y(t) = &+ [y_0 - \frac{2\;\dot{x}_0}{n}] + [6\;x_0 + \frac{4\;\dot{y}_0}{n}]\;\sin(n\;t) \\ &+ \frac{2\;\dot{x}_0}{n}\;\cos(n\;t) - [6\;n\;x_0 + 3\;\dot{y}_0]\;t \end{aligned} \tag{5}$$

$$z(t) = + \frac{\dot{z}_0}{n}\;\sin(n\;t) + z_0\;\cos(n\;t) \tag{6}$$

Based on 3D imaging from a PMD camera the pose estimation algorithm described in the previous section provides relative position vectors at camera frame rate. These data sets are used as initial values $\boldsymbol{r_0} = (x_0, y_0, z_0)^T$ and $\boldsymbol{v_0} = (\dot{x}_0, \dot{y}_0, \dot{z}_0)^T$. The prediction is thus updated with every new incoming pose estimation data set. The prediction of the spacecraft rotational motion (orientation and angular velocity) is based on a linearized approach.

### *2.4 Collision Detection*

With the help of predicted relative trajectories collisions between the spacecraft can be foreseen. Thus an algorithm has been developed that detects eventual collisions along the predicted trajectory. For that reason 3D representations of both spacecraft are created that consist of oriented bounding boxes encapsulating them. This approach shows various benefits. First of all the exact geometry of the target is not required, which might be an advantage since e.g. in OOS missions the target might be damaged or altered over time. So a safety envelope around the target satellite can be created to encounter these deviations. In addition to that this approach requires less computation effort compared to more complex polygon-based Computer-Aided Design (CAD) models and requires minimal additional data to be stored. Besides satellite models consisting of oriented bounding boxes can be created and handled very easily. To detect possible collisions on the future relative trajectory the 3D representations of the spacecraft are moved along their predicted trajectories and geometrical intersection tests (separating axis tests, cf. Ericson (2005)) between the bounding boxes of the two spacecraft are performed at different points in time. A collision is detected, if any of the bounding boxes of the spacecraft are intersecting. In this case the system provides information characterizing the foreseen collision in terms of time, position and orientation. This can act as an alarm during close range maneuvers. If no collision is detected, the prediction stops at a predefined time in the future (e.g. 10 min). Since collision detection is based on pose information generated by the above described algorithm, this procedure is performed for each data set provided (up to 10 times per second). Further results as well as extensive evaluation have been published in Scharnagl et al. (2013) and Regoli et al. (2013).