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The Enhancement of Target Localization Using Ship-Borne Electro-Optical Stabilized Platform

Jaehoon Ha, Byungmo Kang, Kilho Hong, Jungsoo Park

Abstract**—**Electro-optical (EO) stabilized platforms have been widely used for surveillance and reconnaissance on various types of vehicles, from surface ships to unmanned air vehicles (UAVs). EO stabilized platforms usually consist of an assembly of structure, bearings, and motors called gimbals in which a gyroscope is installed. EO elements such as a CCD camera and IR camera, are mounted to a gimbal, which has a range of motion in elevation and azimuth and can designate and track a target. In addition, a laser range finder (LRF) can be added to the gimbal in order to acquire the precise slant range from the platform to the target. Recently, a versatile functionality of target localization is needed in order to cooperate with the weapon systems that are mounted on the same platform. The target information, such as its location or velocity, needed to be more accurate. The accuracy of the target information depends on diverse component errors and alignment errors of each component. Specially, the type of moving platform can affect the accuracy of the target information. In the case of flying platforms, or UAVs, the target location error can be increased with altitude so it is important to measure altitude as precisely as possible. In the case of surface ships, target location error can be increased with obliqueness of the elevation angle of the gimbal since the altitude of the EO stabilized platform is supposed to be relatively low. The farther the slant ranges from the surface ship to the target, the more extreme the obliqueness of the elevation angle. This can hamper the precise acquisition of the target information. So far, there have been many studies on EO stabilized platforms of flying vehicles. However, few researchers have focused on ship-borne EO stabilized platforms of the surface ship. In this paper, we deal with a target localization method when an EO stabilized platform is located on the mast of a surface ship. Especially, we need to overcome the limitation caused by the obliqueness of the elevation angle of the gimbal. We introduce a well-known approach for target localization using Unscented Kalman Filter (UKF) and present the problem definition showing the above-mentioned limitation. Finally, we want to show the effectiveness of the approach that will be demonstrated through computer simulations.

Keywords**—**Target localization, ship-borne electro-optical stabilized platform, unscented Kalman filter.

Jaehoon Ha is with Agency for Defense Development, Yuseong P.O. Box 35, Daejeon, 305-600, Republic of Korea (phone: +82-42-821-4792; fax: +82-42-823-3400; e-mail: jhha2412@gmail.com, woody@add.re.kr).

Byungmo Kang is with Agency for Defense Development, Yuseong P.O. Box 35, Daejeon, 305-600, Republic of Korea (phone: +82-42-821-2217; fax: +82-42-823-3400; e-mail: byungmo83@gmail.com, bmkang@add.re.kr).

Kilho Hong is with Agency for Defense Development, Yuseong P.O. Box 35, Daejeon, 305-600, Republic of Korea (phone: +82-42-821-4335; fax: +82-42-823-3400; e-mail: hkh1221@add.re.kr).

Jungsoo Park is with Agency for Defense Development, Yuseong P.O. Box 35, Daejeon, 305-600, Republic of Korea (phone: +82-42-821-0686; fax: +82-42-823-3400; e-mail: pjs2k@add.re.kr).

I. INTRODUCTION

MANY types of vehicles such as surface ships and UAVs take a use of EO stabilized platforms for their surveillance and reconnaissance [1], [2]. EO stabilized platforms' gimbal has a range of motion in elevation and azimuth which allows it to designate and track a target. The precision of the slant range from the platform to a target acquired by the system can be further improved if a LRF is added to the gimbal. More versatile target localization is required if it is to aid the operation of the weapon systems which are mounted on the same platform. The weapon systems require more accurate target information such as target's location and velocity. The type of moving platforms has a great potential to affect the accuracy of the target information, because the accuracy of the target information depends on diverse component and alignment errors among each component [3]. It is important to acquire the precise altitude information when it comes to the case of flying platforms such as UAVs because there is a high possibility that the target location error increases as the altitude of the platform changes. The target location error increases along with the obliqueness of the elevation angle of the gimbal in the case of surface ships, because the altitude of the EO stabilized platform is supposed to be relatively low. This is in a way of acquiring precise target information on a surface ship.

Not so many researches have been made on ship-borne EO stabilized platforms that are mounted on the surface ship [7], [8] even though many studies on EO stabilized platforms of flying vehicles [3]-[6] are still actively on going these days. In this paper, we deal with target localization method when an EO stabilized platform is located on the surface ship. It is our goal to overcome the limitation caused by the obliqueness of the elevation angle of the gimbal. So, we introduce a well-known approach, UKF for the target localization and present how we are going to achieve our goal. We made an assumption that the surface ships do not move while acquiring the target location just for simplicity throughout the whole paper.

II. KINEMATICS OF TARGET LOCALIZATION

Before starting estimation of target location, we need to understand how to acquire the target location. We adopt the general kinematics of target localization that is presented in [3], [4], and this technical approach is briefly introduced in this section. Firstly, we assume the coordinate frames that include the inertial frame, the mast frame, the body frame, the gimbal frame, and the camera frame. Fig. 1 shows the schematics of the different coordinate frames and provides a conceptual sketch of the EO stabilized platform on the surface ship. The inertial frame is a fixed frame with X_I directed north, Z_I directed toward the center of the earth, and therefore, Y_I directed east. The origins of the mast frame, body frame, gimbal frame, and camera frame are assumed to coincide.

Fig. 1 Schematics of the coordinate frames (Example: USCG Thetis [8])

Secondly, we need to define the homogeneous transformation matrix from frame i to frame j (T_i^j). The transformation from the inertial frame to the mast frame is given by:

$$T_I^M = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & -h \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where x and y mean the north and east locations of the center of the mast, respectively, as measured by its GPS sensor, and h is the altitude of the mast from the ground, which can be obtained by GPS sensor or altimeter. The transformation from the mast frame to the body frame is given by:

$$T_M^B = \begin{bmatrix} c_\theta c_\phi & c_\theta s_\psi & -s_\theta & 0 \\ s_\phi s_\theta c_\psi - c_\phi s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & s_\phi c_\theta & 0 \\ c_\phi s_\theta c_\psi + s_\phi s_\psi & c_\phi s_\theta s_\psi - s_\phi c_\psi & c_\phi c_\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where ϕ, θ, and ψ are the body's roll, pitch, and heading angles, respectively, and $c_\theta = \cos(\theta)$, $s_\theta = \sin(\theta)$. The transformations from the body frame to the gimbal frame and from the gimbal frame to the camera frame are given by:

$$T_B^G = \begin{bmatrix} c_{el} c_{az} & c_{el} s_{az} & s_{el} & 0 \\ -s_{az} & c_{az} & 0 & 0 \\ -s_{el} c_{az} & -s_{el} s_{az} & c_{el} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$T_G^C = \begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

where az and el are denoted by the azimuth angle of rotation about Z_g and the elevation angle of rotation about Y_g, respectively, and T_G^C aligns the camera's frame with that of the gimbal.

In order to localize the target, we need to consider the calibration matrix C which shows the change matrix from pixels to meters in the image frame [9].

$$C = \begin{bmatrix} 0 & f_x & O_x & 0 \\ -f_y & 0 & O_y & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

Finally, the image depth λ means the distance along the camera's optical axis to the target of interest.

$$\Lambda = \begin{bmatrix} \lambda & 0 & 0 & 0 \\ 0 & \lambda & 0 & 0 \\ 0 & 0 & \lambda & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

We need to introduce p_{cc}^I which is the location of the camera's optical sensor in the inertial frame so as to calculate the image depth λ. In addition, $\overline{p}_{obj}^I$ is also needed to estimate λ.

$$p_{cc}^I = \begin{bmatrix} x_{cc}^I \\ y_{cc}^I \\ z_{cc}^I \\ 1 \end{bmatrix} = \left[T_G^C T_B^G T_M^B T_I^M\right]^{-1} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \tag{7}$$

$$\bar{p}_{obj}^I = \begin{bmatrix} \bar{x}_{obj}^I \\ \bar{y}_{obj}^I \\ \bar{z}_{obj}^I \\ 1 \end{bmatrix} = \left[C T_G^C T_B^G T_M^B T_I^M\right]^{-1} q \tag{8}$$

From (7) and (8), we can calculate λ by:

$$\lambda = \frac{-z_{cc}^I}{\bar{z}_{obj}^I - z_{cc}^I} \tag{9}$$

If the LRF is used, the image depth λ can be directly measured because it represents originally the slant range. However, because only one LRF is supposed to be affordable, the rest targets which cannot be designated by the LRF are inevitably estimated by the numerical formula (9). Conclusively, the mathematical relationship between q and p_{obj}^I is as:

$$p_{obj}^I = \left[C T_G^C T_B^G T_M^B T_I^M\right]^{-1} \Lambda q \tag{10}$$

When it comes to the target localization, we are going to use the UKF to estimate the target location because the raw target locations are likely to be deteriorated by various errors.

III. UKF [10], [11]

The generic Kalman filter is not appropriate because the dynamic and measurement models are not linear. In order to apply to the nonlinear problems, two types of method such as the Taylor series based Extended Kalman Filter (EKF) and the unscented transform based UKF can be considered. The EKF solves the problem of nonlinearity with gradual expansion of linear algorithm. However, this can cause large errors, and may lead to divergence of the filter. The UKF solves the same problem without this linearization process, so it is free from the problem of divergence, which is caused by a linear model obtained through Jacobian. And that is why we use the UKF to estimate the target localization because the raw target locations are likely to be deteriorated by various errors. The UKF algorithm is presented in Fig. 2. The details of the UKF algorithm are explained in [10] and [11]

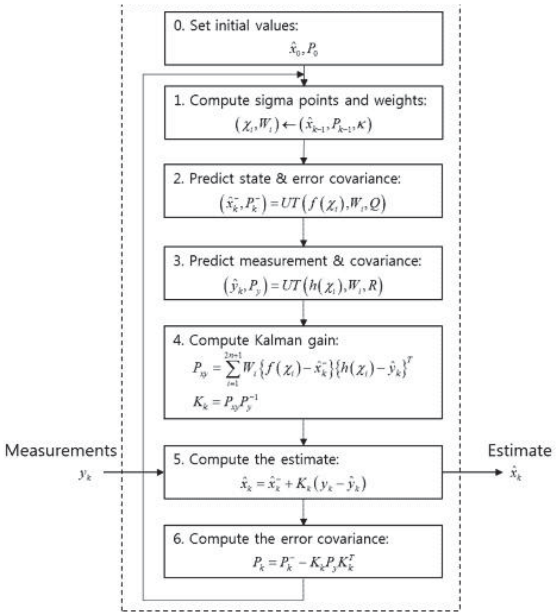

Fig. 2 UKF Algorithm

IV. PROBLEM DEFINITION

The extreme obliqueness of the angle of the target can be happened due to the low altitude when the EO stabilized platform is located on the surface ship. For example, we can conceptually compare the areas imaged by the camera between at the high altitude and the low altitude in Figs. 3 and 4. The low altitude covers the trapezoid-shaped area imaged by the camera, showing the distorted area above the centerline of that area; however, the high altitude does the almost square-shaped area imaged by the camera, so there is less distortion of the area rather than the case of low altitude. This feature takes an effect on the accuracy of the target localization performance.

The main target is always centered on the pixel plane and designated by the LRF. Using the LRF helps the slant range of the main target to be measured as precisely as possible. On the other hand, the sub targets cannot be designated by the LRF and are localized using the estimated image depth. Therefore, the localization performance of the sub targets is supposed to be less accurate than that of the main target. In this paper, we focus to enhance the localization performance of the main target. In the case of the main target, we always slew the gimbal to locate the main target at the center of the pixel plane.

TABLE I
UNCERTAIN QUANTITIES

Error sources	Values
Azimuth and elevation	1 mrad
Roll, pitch, and yaw (stabilization angle)	2 μrad
x, y, and h (platform position)	2 m

We assume the initial position of the target is (4000, 0, 0) as the main target. Fig. 5 shows that the target moves at 10 m/s and towards 185 deg (slightly south east) bearing without errors. A trapezoid-shaped box means the area imaged by camera. The location of the target is supposed to be contaminated by various errors, such as pointing errors, stabilized errors, and platform errors. Table I shows the various error sources and their values. Fig. 6 shows that the asterisks for the target are randomly distributed.

V. SIMULATIONS

When the UKF is applied, the target is localized more accurately than the baseline estimate.

Figs. 7-11 show the UKF estimation results. The root mean square error of the target location is decreased from 81.7 m to 31.5 m. In the case of the target velocity, we can observe that steady state error bound is within about 2 m/s.

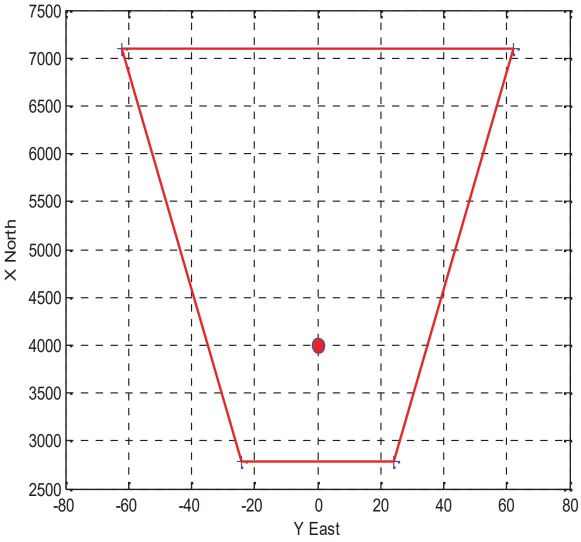

Fig. 3 Area imaged by the camera: low altitude

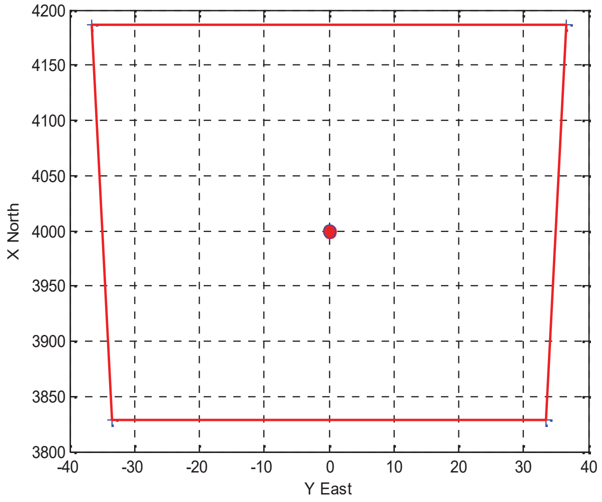

Fig. 4 Area imaged by the camera: high altitude

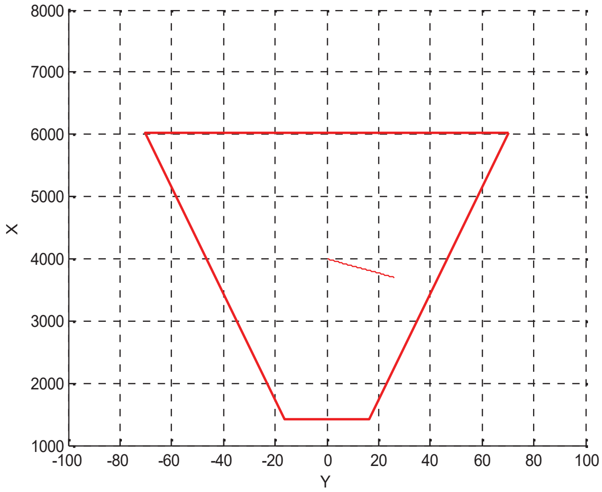

Fig. 5 Position of the target (without errors)

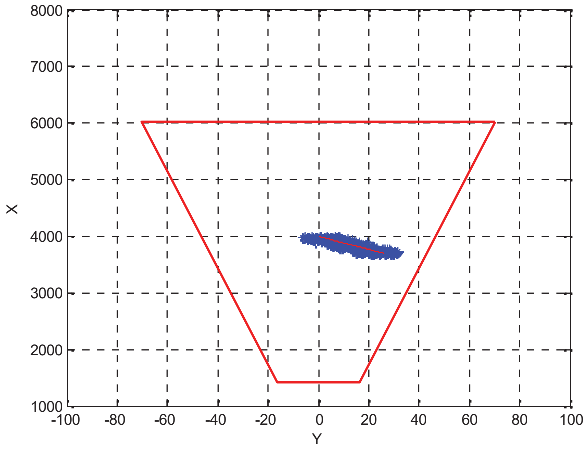

Fig. 6 Distribution to represent the target

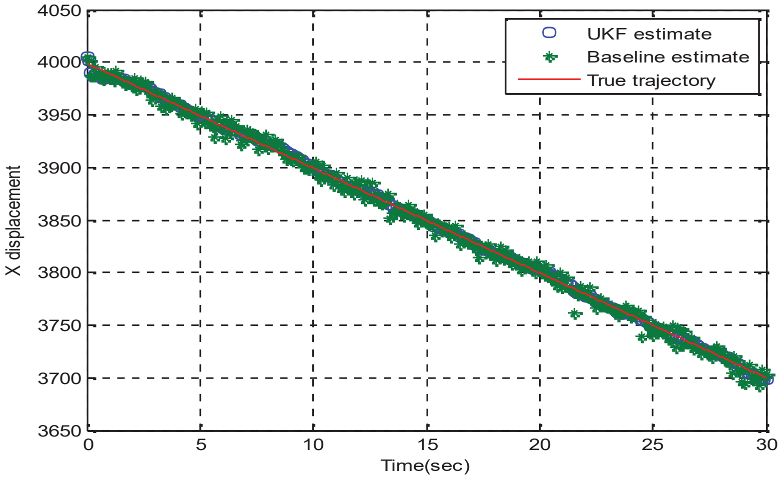

Fig. 7 UKF results (x displacement)

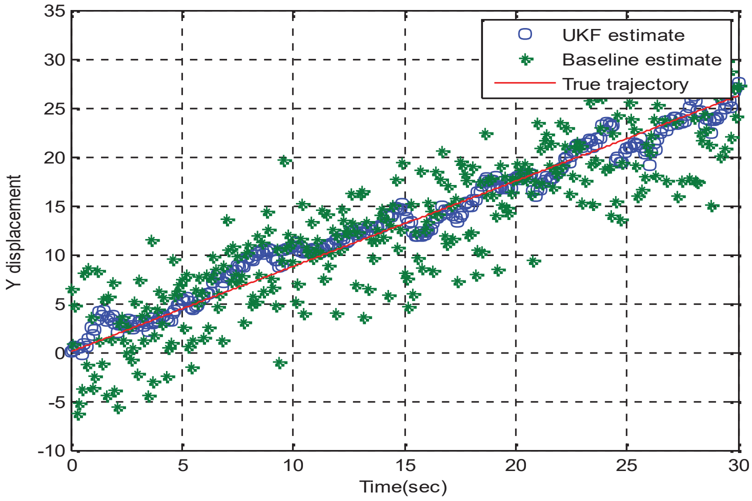

Fig. 8 UKF results (y displacement)

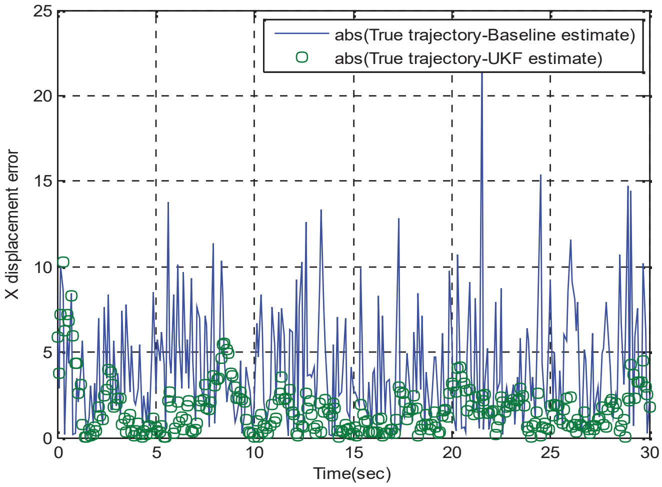

Fig. 9 Localization errors (x displacement)

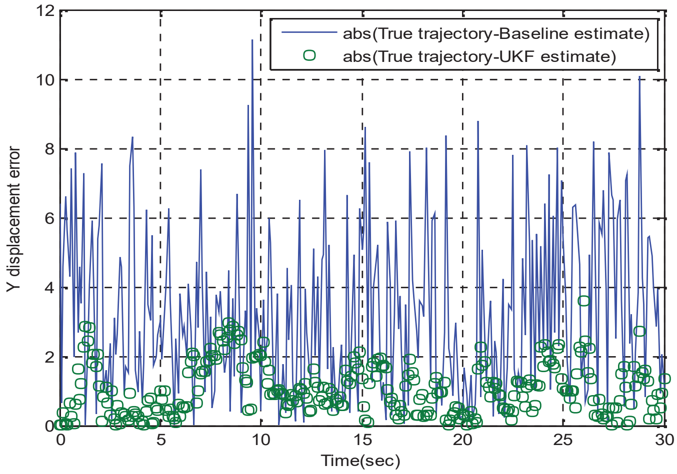

Fig. 10 Localization errors (y displacement)

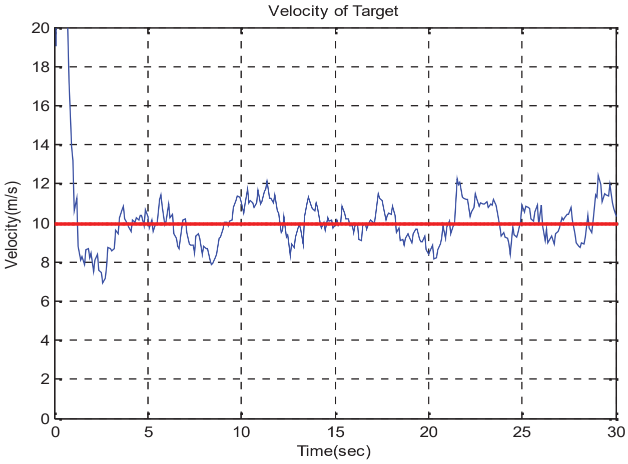

Fig. 11 UKF results (velocity)

VI. CONCLUSION

The functionality of EO stabilized platform is evolving from the surveillance and reconnaissance to acquiring precise target information. In this paper, we studied the mathematical model of acquiring the target localization using the EO stabilized platform. Afterwards, we suggested the UKF in order to estimate more precisely the target location and its velocity. From the computer simulation, we observed the feasibility of the UKF approach. However, we dealt with the case of the main target that is designated by the LRF. For the further research, we need to focus the sub targets that are not designated by the LRF because the LRF is normally only one and it is difficult to designate the main target and sub targets simultaneously. In addition, we need to establish a mathematical relationship among the uncertainty quantities of the platform altitude, elevation angle of the gimbal, and the localization error. When the localization error is predetermined, we can decide the level of uncertainty of the platform altitude, thereby leading us to select a sensor suitable to secure the required error of the platform altitude.

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