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Inertially stabilized platforms using only two gyroscopic measures and sensitivity analysis to unmodeled motion

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Abstract— **Inertially stabilized platforms are subject of interest to different engineering areas, such as telecommunications, robotics and military systems. The objective is to maintain the attitude of a desired object constant despite the movements of a host vehicle, in order to point towards a chosen direction. This paper deals with the platform stabilization problem in the case where only two gyroscopic sensors are available. In this case, certain restrictions to vehicle dynamics are considered. Sensor positioning and sensitivity analysis to unmodeled motion are also discussed. An extension to the visual tracking problem is presented using a class of algorithms for fast digital image registration.**

I. Introduction

Inertially stabilized platforms (ISP) have been widely used in different engineering areas focusing on diverse applications. Such applications include stabilizing cameras, array of sensors and weapons mounted on a moving base[5], [9], [12]. The main control objective is to maintain an object of interest pointing towards a chosen direction, referred to as *line-of-sight* (LOS), despite the base movements. It is, for example, the case where a camera has to be stabilized on a moving robot, meaning that both intentional maneuvers and external disturbances have to be compensated.

This task is usually performed using a set of sensors to measure the host vehicle attitude [4], such as accelerometers, gyros and magnetometers, to provide a robust attitude estimation. Once the attitude is known, compensation is performed using a mechanical structure. The most common structure is the two-axis gimbal [9] which perform rotations in two angles, namely the azimuth and the elevation.

In this work, the platform stabilization problem is considered under restrictions on availability of sensors. It is discussed the case where only two gyroscopic sensors are available to infer the host vehicle attitude. This is an useful concern in mainly two cases: (i) if three axis precision sensors are not available, or are too expensive; and (ii) to consider the possibility of fault, such that stabilization could be achieved even with failure in one sensor axis. Since it is possible to obtain only two angular velocities, some movements cannot be measured, hence can not be compensated either. Consequently, some constraints on the external movements should be taken into account.

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In this way, it is considered the stabilization in the case where the host vehicle motion has no yawing, meaning that only roll and pitch angles have to be compensated. This is a reasonable approximation, for example, to a ship dynamics, where yaw variations are very slow. It can also be an interesting scenario to a ROV (remotely operated vehicle) or UAV (unmanned aerial vehicle) camera stabilization, where compensation of yaw movement could point the camera to parts of the robot itself, restraining the field of view.

It can be shown that, in this situation, only two angular velocities are needed to obtain a complete estimation for the platform orientation, and, consequently, compensation can be achieved. Algorithms to calculate the necessary azimuth and elevation to keep the line-of-sight invariant are presented considering two different alternatives to allocate the gyros. As a natural sequel, the algorithm performances under presence of unwanted movement is analyzed through sensitivity functions.

Stabilization algorithms are also an interesting tool for application in visual tracking systems, since a good stabilization performance would lead to better tracking results [8]. In this work, it is also discussed the integration of stabilized platforms with a visual tracking algorithm based on similarity detection.

II. Problem description

Firstly, the coordinate frames are defined, according to Fig. 1 where **L** is the inertial coordinate frame (local level); and **b** is the vehicle coordinate frame; **B** and **a** are the outer and inner axis frames, respectively. Orientation of the frame i with respect to frame j represented on frame i is denoted by $C_{ij} \in SO(3)$. The angular velocity of frame i with respect to frame j represented on frame i is denoted by $\omega_{ij} \in \mathbb{R}^3$

It is desired to keep the LOS, denoted by $U_L^* \in \mathbb{R}^3$, invariant in a chosen direction with respect to the inertial frame L. To carry this out, the gimbal has to compensate the vehicle attitude C_{bL} using the azimuth α and elevation γ angles, indicated in Fig. 2. Thus, considering a vehicle attitude given by the roll-pitch-yaw representation, i.e.

$$C_{bL} = R_z(\phi)R_y(\theta)R_x(\psi) \tag{1}$$

where $C_{bL} \in SO(3)$; $R_i(k)$ is the elementary rotation around the axis i by an angle k [11]; ψ, θ and ϕ are the vehicle roll, pitch and yaw angles, respectively. The LOS, given in terms of the vehicle attitude C_{aL} is

$$C_{aL} = C_{bL}(\psi, \theta, \phi)\ R_z(\alpha)R_y(\gamma) \tag{2}$$

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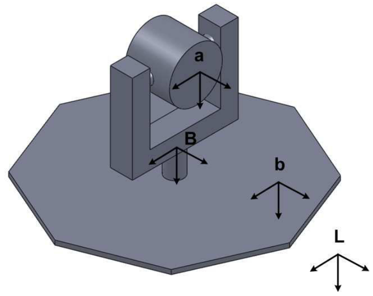

Fig. 1. Coordinate frames adopted

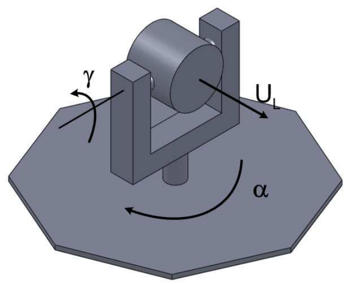

Fig. 2. Compensation angles and line-of-sight direction

where the LOS is the orientation matrix C_{aL} first column [13]. With $e_x^T = [1,\ 0,\ 0]$, it is

$$U_L = C_{aL}\ e_x = C_{bL}(\psi,\theta,\phi) R_z(\alpha) R_y(\gamma)\ e_x \quad (3)$$

It is considered that the desired line-of-sight U_L^* is chosen by the operator in the moment that platform stabilization is triggered in a certain attitude,

$$C_{aL}^* = C_{bL}(\psi^*,\theta^*,\phi^*)\ R_z(\alpha^*) R_y(\gamma^*) \quad (4)$$

where ψ^*, θ^*, ϕ^*, α^* e γ^* are the angles when stabilization starts. Thereby, the desired LOS is given by:

$$U_L^* = C_{aL}^* e_x \quad (5)$$

Note that since the objective is to maintain only a direction invariant, the LOS, a mechanism with two degrees of freedom is enough (rotations around the LOS are not compensated). Then, the first step is to determine the azimuth α and elevation γ angles to which U_L is aligned with U_L^*, hence, from (3) and (5), the following equation has to be satisfied

$$C_{bL}(\psi,\theta,\phi)\ R_z(\alpha) R_y(\gamma)\ e_x = C_{aL}^*\ e_x \quad (6)$$

From (6), one has, where U_b^* is the vector defining the LOS in the vehicle frame (b):

$$R_z(\alpha)\ R_y(\gamma)\ e_x = C_{bL}^T(\psi,\theta,\phi)\ U_L^* = U_b^* \quad (7)$$

The expression to U_b^* can be obtained by means of elementary rotation matrices, considering that[1]:

$$R_z(\alpha) R_y(\gamma)\ e_x = [c_\alpha c_\gamma \quad s_\alpha s_\gamma \quad -s_\gamma]^T \quad (8)$$

[1]It is chosen the abbreviated notation s_α, c_α and tg_α denote $\sin(\alpha)$, $\cos(\alpha)$ and $\tan(\alpha)$, respectively.

On the other hand, knowing that:

$$U_b^* = C_{bL}^T(\psi,\theta,\phi)\ U_L^* = [x_1 \quad x_2 \quad x_3]^T$$

the azimuth and elevation α and γ can be calculated as:

$$\alpha = \arctan(x_2/x_1)\,; \quad \gamma = \arcsin(-x_3) \quad (9)$$

However, the attitude matrix $C_{bL}(t)$ has not been determined yet. It can be calculated by means of a numeric integration of the vehicle angular velocity $\omega_{bL}(t)$ [10], [6]. For an infinitesimal angular rotation $e^{\Delta t \hat{\omega}_{bL}(t)}$, one has:

$$C_{bL}(t+\Delta t) = C_{bL}(t)\ e^{\Delta t\ \hat{\omega}_{bL}(t)} \quad (10)$$

where Δt is the sampling interval, and $\hat{\omega}_{bL} = \omega_{bL}\times$, with $\times$ denoting the cross product. Since for a given vector $\omega^T = [\omega_1,\ \omega_2,\ \omega_3]$, one has:

$$w\times = \hat{w} = \begin{bmatrix} 0 & -w_3 & w_2 \\ w_3 & 0 & -w_1 \\ -w_2 & w_1 & 0 \end{bmatrix}; \quad \hat{w} = -\hat{w}^T$$

The matrix $e^{\Delta t\ \omega_{bL}(t)\times}$ may be calculated using Rodrigues formula [6]:

$$e^{\hat{\omega}_{bL}\Delta t} = I + \frac{\hat{\omega}_{bL}}{\|\omega_{bL}\|}\ \sin(\Delta\omega) + \frac{\hat{\omega}_{bL}^2}{\|\omega_{bL}\|^2}\ (1-\cos(\Delta\omega)) \quad (11)$$

where $\Delta\omega = \|\omega_{bL}\|\,\Delta t$ and I is the identity matrix.

Note that to calculate the orientation C_{bL}, the angular velocity ω_{bL} has to be completely known at each instant t, as shown by Eq. (10). In fact, with a complete set of gyroscopic measures available, this velocity is directly obtained after a coordinate frame change and the the problem of calculating the azimuth and elevation angles is solved in a straightforward manner from C_{bL}. Without loss of generality, it is considered that $C_{bL}(0) = I$.

In this work, it is considered the availability of only two gyros, meaning it is possible to measure angular velocities around two axis merely. Under this constraint, it is desired to find a way to determine all three components of the body velocity ω_{bL}.

Since only two velocities are measured, an estimate ω_e for the unavailable measure should be obtained. This is only possible if additional assumptions are considered, e.g. in the case where there is no variation of yaw or where only roll and pitch should be compensated. With this estimate, it is possible to calculate the body velocity ω_{bL} needed. Indeed, it is possible to write ω_{bL} as a function of the estimate for the unknown measure, the vehicle attitude and the compensation angles. It takes the following form:

$$\omega_{bL} = A(q)\ \omega_m + B(q)\ \omega_e + D(q)\ \dot{q} \quad (12)$$

$$\omega_e = K(\vartheta,q)\ \omega_m + L(\vartheta,q)\ \dot{q} \quad (13)$$

and consequently,

$$\omega_{bL} = (A(q)+B(q)K(\vartheta,q))\,\omega_m + (B(q)L(\vartheta,q)+D(q))\,\dot{q}$$

where $\omega_m \in \mathbb{R}^2$ are the measured velocities, $\omega_e \in \mathbb{R}$ is the unmeasured velocity, wherefore calculated, $q = [\alpha \quad \gamma]^T$ and $\vartheta = [\psi \quad \theta \quad \phi]$. The velocity ω_{bL} can be determined knowing the functions $A(q) \in \mathbb{R}^{3\times 2}, B(q) \in \mathbb{R}^{3\times 1}, D(q) \in \mathbb{R}^{3\times 2}, K(\vartheta) \in \mathbb{R}^{1\times 2}$ and $L(\vartheta) \in \mathbb{R}^{1\times 2}$.

As discussed before, it is considered that the vehicle yaw angle is constant, meaning that only roll and pitch are compensated.

To relate roll, pitch and yaw rates with the vehicle angular velocities ω_{bL} with respect to the inertial frame, the Jacobian is used [6], as it follows:

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix}0 & \dfrac{\sin(\psi)}{\cos(\theta)} & \dfrac{\cos(\psi)}{\cos(\theta)}\\ 0 & \cos(\psi) & -\sin(\psi)\\ 1 & \tan(\theta)\sin(\psi) & \tan(\theta)\cos(\psi)\end{bmatrix}\begin{bmatrix}\omega_{bL}^x\\ \omega_{bL}^y\\ \omega_{bL}^z\end{bmatrix} \tag{14}$$

The block diagram of Fig. 3 shows the proposed inertial stabilization strategy. In this figure, the vector elements of the angular velocities are denoted by ω_{m1} e ω_{m2}.

The azimuth α e and elevation γ are calculated and then used as reference signals to drive two motors that perform this compensation. To carry this out, the well-known proportional-proportional-integral (P-PI) controller is employed.

III. Roll and pitch stabilization

To a null yaw rate, the stabilization problem consists only in stabilizing pitch and roll. Both direct and indirect stabilization are considered, whether gyros are allocated on the gimbal outer axis (frame B) or are mounted on the gimbal inner axis (frame a) [7].

A. Indirect stabilization: gyros on the outer axis

The vehicle angular velocity with respect to the inertial frame can be obtained by the gyro measures after a coordinate frame change. In fact, it is needed to correct the gimbal azimuth rotation, since this movement also reflects on the measure of ω_{BL}. Thereby, it is possible to write:

$$\omega_{bL} = \omega_{bB} + C_{Bb}(\alpha)\ \omega_{BL} \tag{15}$$

with $\omega_{bB} = [0, 0, -\dot{\alpha}]$, and $C_{Bb} = R_z(\alpha)$.

Note that the angular velocity of the gimbal outer axis with respect to the inertial frame, ω_{BL}, is not completely measured. Since only two gyros are available, only two components of ω_{BL} are directly obtained.

Considering that vehicle motion has no variation of yaw and from (14), the following result can be obtained considering $\dot{\phi} \equiv 0$:

$$\frac{\sin(\psi)}{\cos(\theta)}\ \omega_{bL}^y + \frac{\cos(\psi)}{\cos(\theta)}\ \omega_{bL}^z = 0$$

Thus, it is possible to write the z component of the vehicle angular velocity in terms of y component.

$$\omega_{bL}^z = -\tan(\psi)\ \omega_{bL}^y \tag{16}$$

Note that the roll can be calculated using the orientation matrix C_{bL}, $\psi = \arctan(C_{bL}(3,2)/C_{bL}(3,3))$, where $C_{bL}(i,j)$ is the element of C_{bL} on the line i and column j. Yet, one should note that despite the presence of a singularity in (16) to $\psi = \pi/2$, this condition does not represent a practical constraint, since this scenario is not allowed by the vehicle operation. From Eq. (15) and (16) it is possible to infer that the component ω_{bL}^y depends only on two measures, namely ω_{BL}^x and ω_{BL}^y. Explicitly, it is possible to obtain the body angular velocity completely with these two measures and Eqs. (12)-(23) with appropriate matrices:

$$A = \begin{bmatrix}c_\alpha & -s_\alpha\\ s_\alpha & c_\alpha\\ 0 & 0\end{bmatrix},\ B = \begin{bmatrix}0\\0\\1\end{bmatrix},\ K = \begin{bmatrix}-tg_\psi s_\alpha\\ -tg_\psi c_\alpha\end{bmatrix}^T \tag{17}$$

$$L = \begin{bmatrix}1 & 0\end{bmatrix},\ D = \begin{bmatrix}0 & 0 & -1\\ 0 & 0 & 0\end{bmatrix}^T \tag{18}$$

And $\omega_m = [\omega_{bL}^x\ \ \omega_{bL}^y]^T$ and, consequently, $\omega_e = \omega_{bL}^z$.

Thereby, with Eq. (17)-(18) it is possible to determine completely the vehicle angular velocity with respect to the inertial frame with only two gyros positioned along the x and y axis to a constant yaw angle. This result is consistent since there is no rotation around the z axis in this case.

As discussed in the previous section, information of body velocity with respect to the inertial frame ω_{bL} allows the determination of the platform orientation, from which the compensation angles α e γ to achieve stabilization are then obtained. These angles are used as reference signals to azimuth and elevation motor control loops.

B. Direct stabilization: gyros on the inner axis

In the case where gyros are allocated in the inner axis, there are two rotations to be considered to refer measured velocities in the body frame due to the elevation angle γ. Note that now the measured velocity is ω_{aL}.

$$\omega_{bL} = \omega_{ba} + C_{ab}(\alpha,\gamma)\ \omega_{aL} \tag{19}$$

where $\omega_{ba} = [\dot{\gamma}s_\alpha, -\dot{\gamma}c_\alpha, -\dot{\alpha}]^T$ and $C_{ab}(\alpha,\gamma) = R_z(\alpha)\ R_y(\gamma)$.

From Eq. (14), (16) and (27) it is possible to derive an expression to the z component to the vehicle velocity:

$$\omega_{bL}^z = -tg_\psi(-\dot{\gamma}c_\alpha + s_\alpha c_\gamma \omega_{aL}^x + c_\alpha \omega_{aL}^y + s_\alpha s_\gamma \omega_{aL}^z)$$

Consequently, the angular velocity ω_{aL}^z is:

$$\begin{aligned}\omega_{aL}^z \quad = \quad & \frac{\dot{\alpha} + \dot{\gamma} tg_\psi c_\alpha}{\Delta_1} + \\ & + \frac{s_\gamma - tg_\psi s_\alpha c_\gamma}{\Delta_1}\omega_{aL}^x + \frac{-tg_\psi c_\alpha}{\Delta_1}\omega_{aL}^y\end{aligned} \tag{20}$$

with $\Delta_1 = c_\gamma + tg_\psi s_\alpha s_\gamma$.

This result may be written under the form (12)-(23) with:

$$A = \begin{bmatrix}c_\alpha c_\gamma & -s_\alpha\\ s_\alpha c_\gamma & c_\alpha\\ -s_\gamma & 0\end{bmatrix},\ B = \begin{bmatrix}c_\alpha s_\gamma\\ s_\alpha s_\gamma\\ c_\gamma\end{bmatrix} \tag{21}$$

$$K = \frac{1}{\Delta_1}\begin{bmatrix}-tg_\psi s_\alpha c_\gamma + s_\gamma\\ -tg_\psi c_\alpha\end{bmatrix}^T \tag{22}$$

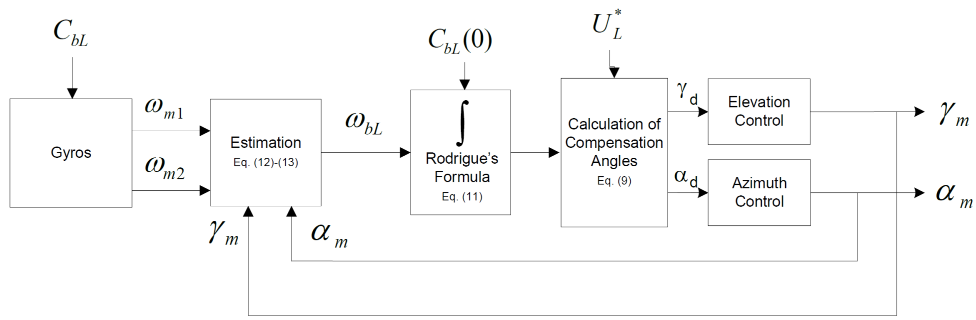

Fig. 3. Block diagram with the proposed inertial stabilization strategy

$$\begin{bmatrix}1 & tg_{\psi}c_{\alpha}\end{bmatrix},\ D = \begin{bmatrix}0 & 0 & -1\\ s_{\alpha} & -c_{\alpha} & 0\end{bmatrix}^T \tag{23}$$

Similarly to the previous case, $\omega_m = [\omega_{bL}^x \quad \omega_{bL}^y]^T$ and $\omega_e = \omega_{bL}^z$. So, the vehicle velocity with respect to the inertial frame can be completely determined with only two measures. From Eq. (20) it is possible to note that, in this case, there is also the presence of a singularity, this time in the case where $\gamma = \pm\pi/2$. However, this is the scenario where the line-of-sight is pointing towards zenith/nadir, totally in the vertical direction. Likewise, this is not under the operation possibilities.

Note that the component ω_{bL}^z is calculated based on measures of ω_{aL}^x and ω_{aL}^y. The gyros have to be positioned taking that into account, meaning they shall be allocated along the x and y axis.

Once the velocity ω_{bL} is determined, the azimuth and elevation angles α e γ that allow compensation may be obtained in a straightforward manner and compensation is performed by the gimbal motors, and thus, as previously, stabilization is achieved.

IV. Sensitivity to undesired motion

In order to evaluate performance of the presented algorithms, a sensitivity analysis is developed. Using the inverse Jacobian (14), it is possible to obtain an expression to the ideal angular velocity ω_{BL}^z, that is not measured, in terms of roll, pitch and yaw rates. It is possible, thus, to compare the obtained estimate of ω_{BL}^z with the expected value, so that the error on ω_{bL} can be calculated.

A. Indirect stabilization in the presence of yaw movement

The expression to ω_{BL}^z can be obtained by the coordinate frame change (15) to express ω_{bL} in the body frame. Through (15) and the inverse of (14), it leads to

$$\omega_{BL}^z = \cos(\psi)\cos(\theta)\dot{\phi} - \sin(\psi)\dot{\theta} + \dot{\alpha} \tag{24}$$

The estimate error is, thereby, the difference between the estimated and the real value of ω_{BL}^z which may be obtained as a function of ψ, θ, ϕ and their derivatives. The estimated value ω_e is obtained from (23), which means that the difference between estimated and real values is:

$$\Delta\omega_{BL}^z = \omega_e - \omega_{BL}^z = -\frac{\cos(\theta)}{\cos(\psi)}\dot{\phi} \tag{25}$$

so that in needed angular velocity, results in:

$$\tilde{\omega}_{bL} = \begin{bmatrix}0 & 0 & -\frac{\cos(\theta)}{\cos(\psi)}\dot{\phi}\end{bmatrix}^T \tag{26}$$

Note that this result is a function of $\dot{\phi}$, which is consistent, since the error should be zero if external movement has no yaw angle variation. Another point to be observed is that, in this configuration of sensor position, only the z component of the angular velocity ω_{bL} is affected, since the compensation angles does not influence the velocity measured by the gyros. This behavior can be evaluated by simulation, as shown in next section.

B. Direct stabilization in the presence of yaw movement

Repeating the same steps to roll and pitch direct stabilization, the result for estimate error is obtained through the following change of coordinate frames:

$$\omega_{bL} = \omega_{ba} + C_{ab}(\alpha,\gamma)\ \omega_{aL} \tag{27}$$

The inverse of Eq. (14) and (27) give

$$\Delta\omega_{aL}^z = -\frac{\cos(\theta)}{\cos(\gamma)\cos(\psi) + \sin(\psi)\sin(\alpha)\sin(\gamma)}\dot{\phi} \tag{28}$$

so that, to the estimated velocity:

$$\tilde{\omega}_{bL} = \frac{1}{c_{\gamma}c_{\psi} + s_{\psi}s_{\alpha}s_{\gamma}}\dot{\phi}\begin{bmatrix}c_{\alpha}s_{\gamma}c_{\theta}\\ s_{\alpha}s_{\gamma}c_{\theta}\\ c_{\theta}c_{\gamma}\dot{\phi}\end{bmatrix} \tag{29}$$

Note that, in this case, all components of ω_{bL} are affected by the measuring error, as a consequence of the configuration of sensor position, which may be misaligned with the base according to the azimuth and elevation angles. It is interesting to note that if α and γ are zero, when frames **a** and **B** are aligned, this result takes the form of (26).

V. Extensions to visual tracking

This stabilization technique can be integrated to a visual tracking system. It is desired to command the gimbal with a camera in way that the system is able recognize and follow a chosen object of interest. To this end, algorithms concerning image registration can be applied [2], [3] [14] to determine the object position.

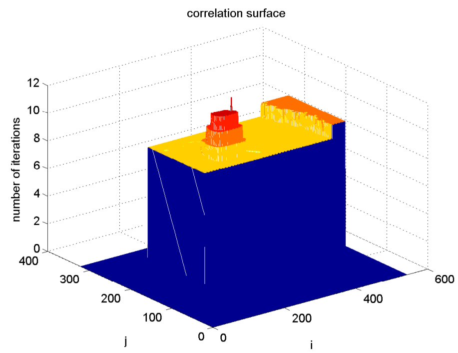

Fig. 4. Typical correlation surface between reference image W and a general frame S

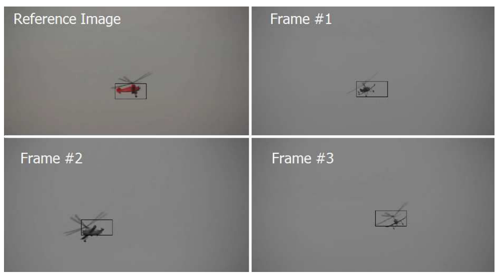

Fig. 5. Results showing successful recognition of the object selected in the first frame (top left) in three different frames.

In this work, a similarity detection algorithm is employed. It can be obtained using a class of algorithms called Sequential Similarity Detection Algorithm (SSDA) [1] which consists in calculating, at each sample time, the correlation between the reference image W with the object to be identified and several candidate sets S_M, which are subsets of the acquired image S. This technique employs a comparison error which is less costly than classical correlation. Candidates are chosen based on the number of iterations needed to reach a constant chosen threshold T on the acumulated error.

A variant of the SSDA is the so called Monotonic Increasing Threshold Algorithm (MITSA), which quickly discards weak candidates by increasing T at each iteration. The number of iterations r needed to reach T is saved to each windowing pair, and a correlation surface $I(i,j)$ is generated, where i and j are the coordinates of the top left corner of each subset S_M.

A typical resulting correlation surface can be seen in Fig. 4, featuring a peak that indicates de coordinates i and j of the candidate set S_M with larger correlation. Also, Fig. 5 shows the chosen candidates S_M for different frames S which where compared to the reference seen in the top left. Note that the object was successfully recognized in all scenarios. Once the position of the object is determined in the camera frame, the new line-of-sight can be calculated as $U'_L = U^*_L + [0 \; e_y \; e_z]$, where e_y and e_z represent the distance of the object to the center of the camera frame. The x component is zero since the pinhole assumption is taken, where image plane is considered orthogonal to the camera line-of-sight and a given focal distance. This allows the location of the target using only two coordinates.

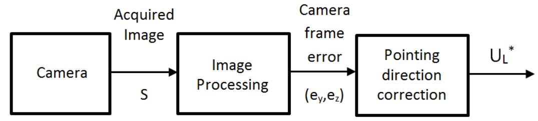

Fig. 6. Integration of visual tracking and stabilization algorithms

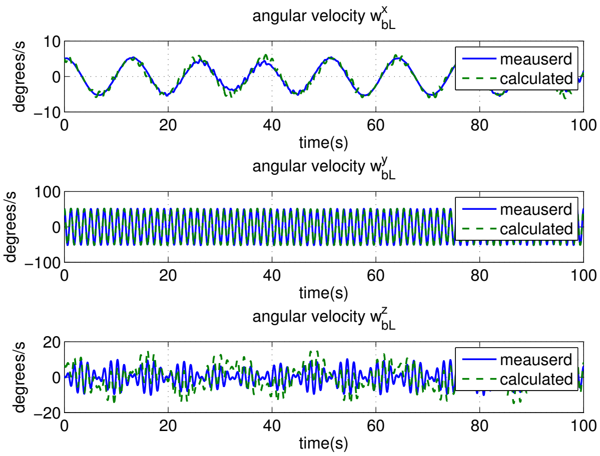

Fig. 7. Comparison between components of angular velocity ω_{bL} in direct stabilization in the presence of yaw variation

The new line-of-sight is used as reference in the previously discussed stabilization algorithm. This idea is represented by the Fig. 6

VI. Simulation Results

By means of a simulation, it is possible to evaluate stabilization performance in ideal conditions an in presence of unwanted yaw movement. We consider an external motion profile chosen to reproduce real motion of the platform used in the experiments, described by $\psi = 10.5\sin(0.0789t)$, $\theta = 6.5\sin(0.0718t)$ and $\phi = 15.2\sin(0.0628t)$ (in degrees).

The obtained ω_{bL} in the indirect stabilization if the platform is submitted to a yaw variation is very close to the direct one, except that only ω^z_{bL} is affected by the unmodeled dynamics. Fig. 7 show the result for the direct stabilization, where it is possible to note that all components of ω_{bL} are affected.

For a better performance evaluation, an angular error can be defined as $e_{ang} = \arccos(U^*_L \cdot U_L)$, that is, the angle between the desired and the obtained line-of-sight. Evaluating this error to both cases, the result is similar, with maximum values under $20°$ as shown in the top of Fig. 8.

Comparing to the precision obtained in the ideal case, seen in the bottom of Fig. 8, this represents a difference greater than 20 times. With no yaw motion, stabilization errors are lower than $0.86°$. Despite the fact that this is indeed a significant difference in relative terms, the absolute error obtained in the case where unwanted motion

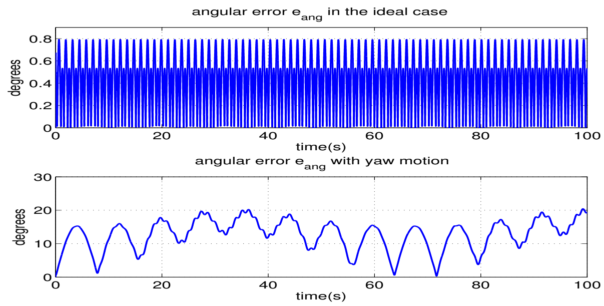

Fig. 8. Angular error in ideal conditions (top) and in the presence of unwanted motion (bottom)

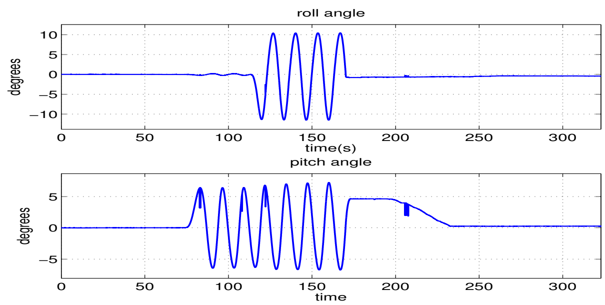

Fig. 9. Roll (top) and pitch (bottom) angles

is present is not of great concern to applications as ROV's or UAV's. This is sufficient to keep objects of interest within a desired field-of-view.

VII. Experimental Results

In order to evaluate the presented algorithms, experiments were performed using a two-degrees of freedom Stewart platform. The gimbal is submitted to roll and pitch external movements as shown by Fig. 9. Compensation angles obtained are show in Fig. 10.

To give a better idea of the obtained performance, the angular error can be calculated with the previous information. This result is shown in Fig. 11. It is possible to note that a good stabilization precision can be obtained, since all error values are below $3.5°$. Furthermore, note that roll and pitch seen in Fig. 9 are not completely smooth, with the presence of small peaks. Since this does not match the platform movement, these might be caused by numeric

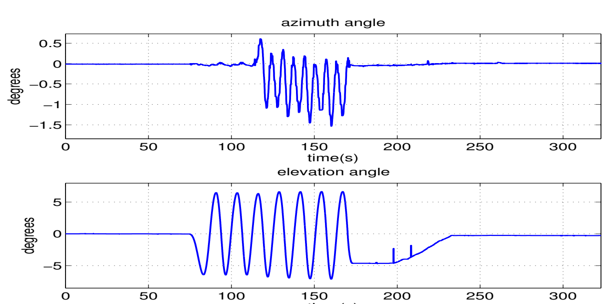

Fig. 10. Azimuth (top) and elevation (bottom) angles

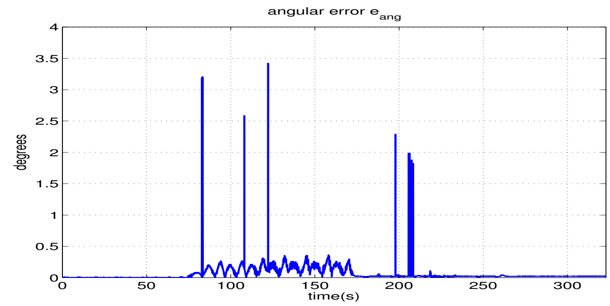

Fig. 11. Angular line-of-sight error

errors, and this reflects in the calculated angular error. Taking this into account, the obtained errors are below $0.5°$, which is a very reasonable precision result.

VIII. Conclusions

This work presented algorithms to deal with inertially stabilized platforms and visual tracking when only two gyroscopic sensors are available. The objective is to keep the line-of-sight invariant despite the motion of a host vehicle. A vehicle with slow yaw variation is considered for which only roll and pitch has to be compensated, such as in ships or some autonomous robots. The experimental results show that stabilization is possible with good accuracy and that a reasonable result may be achieved even in the presence of unmodeled motions. A sensitivity analysis was used to quantify the errors introduced by unwanted movements. Extensions to visual tracking are presented using a similarity detection algorithm, showing that these algorithms can be integrated in such applications.

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