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A400M Image Processing Methodology to Calculate Relative Speed in Air to Air Refuelling

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Abstract:

The A400M deploys the hose and drogue to refuel fixed wind aircrafts and helicopters. This capacity called “air to air refuelling” provides multiple operations at long distances from home base. The helicopter must do contact at a reasonable speed within certain limits that allows a good coupling between the receiver probe and the tanker drogue. The relative speed between the tanker and the receiver is called closure rate.

This paper will explain the methodology used for this closure rate calculation and the flight test means. In general terms this process is based on virtual testing to validate the overall process, an onboard camera installed in the tanker and image processing algorithms developed in-house for the final calculations.

The outputs of this method are the 6-degrees of freedom of the receiver relative to the tanker reference axis, the speeds derived from that trajectory and a video with augmented reality to validate the calculated trajectory. This methodology was used to generate evidences to the certification process in those flight test points when the closure rate is extreme.

Key words: closure rate, air to air refuelling, image processing, augmented reality, photogrammetry.

1. Introduction

The A400M deploys the hose and drogue to refuel fixed wind aircrafts and helicopters. This capacity called “air to air refuelling” provides multiple operations at long distances from home base. The helicopter must do contact at a reasonable speed within certain limits that allows a good coupling between the receiver probe and the tanker drogue. This difference of the two velocities between the tanker and the receiver is called closure rate.

This paper will explain the methodology used for this closure rate calculation between the A400M and the helicopters. In general terms this process is based on virtual testing to validate the overall process, an onboard camera installed in the tanker and image processing algorithms developed in-house for the final calculations.

2. Test means

2.1. Tanker

Flight tests were performed on an A400M with the following AAR characteristics:

- Underwing pods
- Hoses
- Drogue
- Video cameras in fuselage

2.2. Receiver

France air force provided the Eurocopter Caracal, now called Airbus Helicopters H225M, for these flight tests. The A400M contract requires refuelling two helicopters simultaneously (See Fig. 1).

Fig. 1. A400M refuelling two H225M. View from chase aircraft.

2.3. Camera

The A400M development prototypes used for these flight tests have several cameras but for the closure rate calculation was used just one camera placed under the fuselage.

Characteristics of the camera:

- Color
- Full high definition
- 25 frames per second
- Time synchronization with aircraft data

This camera covers the approaching of the helicopters to the drogues (See Fig. 2).

Fig. 2. Caracal view from camera under fuselage.

2.4. Simulation

Simulate the refuelling operation is crucial for the success of the flight tests. A geometric compatibility study is done with the different refuelling positions in order to characterise the risk of the operation (See Fig. 3).

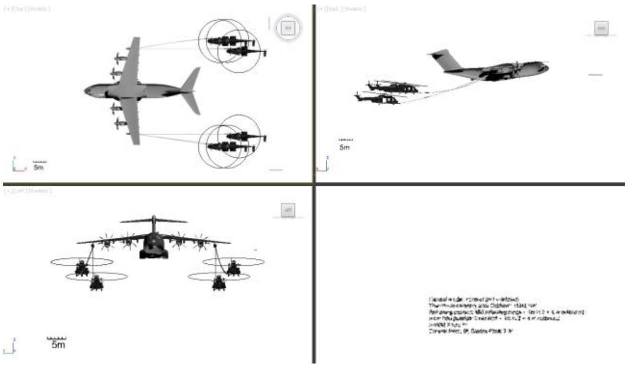

Fig 3. Geometric compatibility study.

Simulation also allows to render videos (See Fig. 4) from onboard cameras installed in the tanker in order to validate the methodology before the real flight tests.

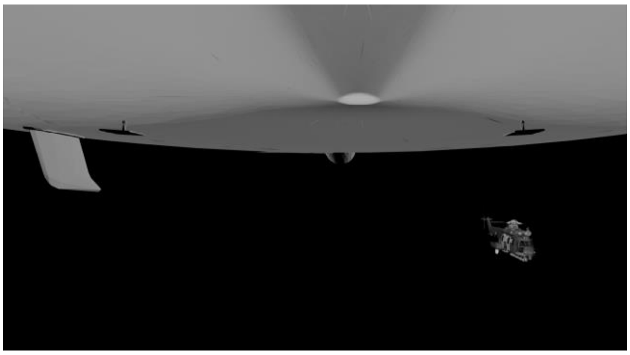

Fig. 4. Rendered image from onboard camera in the tanker.

3. Calibration and positioning of the camera

Using the 3DStudio Max software for scene simulation, the camera is initially positioned in order to cover the approaching of the helicopters to the drogues (See Fig. 4).

To calculate the receiver trajectory in tanker axis reference system it is necessary to position and calibrate the tanker camera. The camera position will be referred to the tanker reference system.

3.1. Tanker reference system

To define this tanker reference system it is necessary to know the coordinates of at least three A400M reference marks, provided by FTI design office (See Fig. 5 & 6).

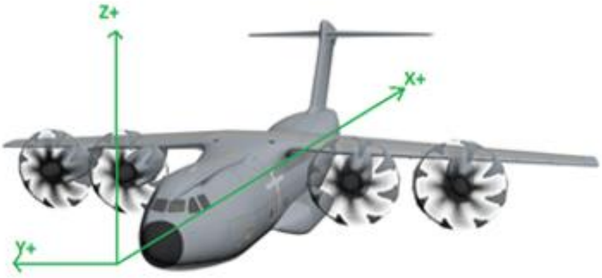

Fig. 5. A400M Tanker reference system.

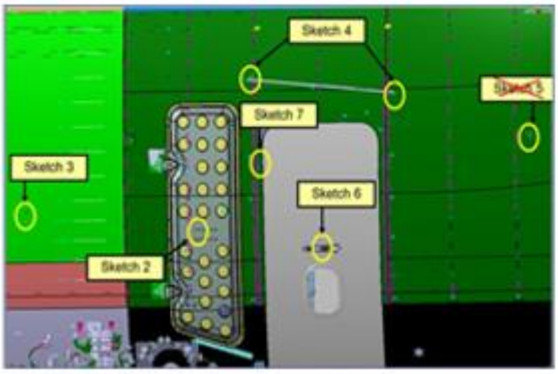

Fig. 6. A400M reference marks.

The algorithm of the closure rate calculation needs to start with the position and angles of the camera relative to the tanker reference system.

3.2. Camera calibration

The aim of the calibration process is to obtain the intrinsic optical parameters of the camera, more specifically of its lens, like focal length, principal point and distortion.

This has been done by means of Jean-Yves Bouguet's calibration toolbox [3]; taking pictures of a checked board of known dimensions (16x9 squares of 80mm) in different positions, varying distances and angles (See Fig. 7).

Fig. 7. Camera calibration.

3.3. Marks respect to the tanker reference system

Special stickers are used as marks by placing them within the cameras' visible field. With the aid of a tachymeter (See Fig. 8), the positions of the camera marks (See Fig. 9) and the reference marks (See Fig. 6) are measured in tachymeter coordinates. The position of the reference marks in tanker reference system are introduced manually in the software of the tachymeter, with this information the software of the tachymeter will transform the camera marks to the tanker reference system.

Fig. 8. Tachymeter used to measure marks in the aircraft.

Fig. 9. Calculation position and attitude of the camera using NEOS software.

3.4. Camera position and angles respect to the tanker reference system

The camera position and angles in tanker reference system is calculated through image processing and photogrammetry algorithms developed in-house in a software called NEOS.

NEOS software contains a function, based on the OpenCV solvePnP method [4]. The inputs of this calculation are the results from the camera calibration, camera marks in tanker reference system and 2D pixel coordinates of these marks (See Fig. 9).

4. Methodology to generate the closure rate

The helicopter must make contact at a reasonable speed within certain limits that allows a good coupling between the receiver probe and the tanker drogue. A minimum speed is required to produce a good coupling. A high speed can produce instabilities in the hose.

Measure the closure rate is part of the certification and qualification process. This section will explain the methodology used for this calculation between the A400M and the helicopters.

The closure rate will be derived from the receiver trajectory in tanker reference system. The trajectory calculated corresponds to one second before and after the contact. The section 4.1 will be applied in each frame in order to get the complete trajectory, the rest of the steps will work with the full trajectory to produce the final closure rate.

4.1. Calculate receiver position/angles in tanker reference system

4.1.1. Select marks in the receiver

NEOS needs at least four marks to calculate the 6DOF of the object. More marks are recommended for having greater accuracy and more robust solutions (See Fig. 10). Others recommendations to take into account are:

- Avoid coplanar marks as much as possible
- Maximize the space between marks
- Select marks that facilitate the tracking
- Avoid marks that can be hidden by others parts in the scene
- The 3D positions of the selected marks in the receiver reference system has to be well known
- Chose the geometric center of the receiver as the origin in the receiver reference system
- Select marks that produce minimum projection error (See Section 4.1.9)

Fig. 10. Marks in red selected by the user in the receiver.

4.1.2. Build transformation matrix from camera axis to receiver axis

This process calls the OpenCV method solvePnP [4] generally used in pose estimation, in this case it is used to estimate the orientation of the receiver based on the 2D image.

Inputs:

- Selected marks from the receiver in receiver reference system
- 2D pixel coordinates of these marks
- Camera calibration

Outputs:

- Transformation matrix from camera axis to receiver axis

4.1.3. Build transformation matrix from receiver axis to camera axis

Compute the inverse of the matrix of the last step.

Inputs:

- Transformation matrix from camera axis to receiver axis

Outputs:

- Transformation matrix from receiver axis to camera axis

4.1.4. Build transformation matrix from camera axis to tanker axis

Compute the rotation matrix compliant with the Tait-Bryan convention [5] followed by the camera translation. The following Python code shows this operation:

```
roll = cam.phi
pitch = cam.theta
yaw = cam.psi

R_x = np.array([[1, 0, 0],
                [0, math.cos(roll),
math.sin(roll)],
                [0, -
math.sin(roll), math.cos(roll)]])

R_y = np.array([[math.cos(pitch),
0, -math.sin(pitch)],
                [0, 1, 0],
                [math.sin(pitch),
0, math.cos(pitch)]])

R_z = np.array([[math.cos(yaw),
math.sin(yaw), 0],
                [-math.sin(yaw),
math.cos(yaw), 0],
                [0, 0, 1]])

R = np.dot(R_x, np.dot(R_y, R_z))

# Create rotation/translation
matrix
# Create identity matrix 4x4
R_4x4 = np.identity(4)
# Add rotation matrix
R_4x4[0:3, 0:3] = R
R_4x4[:, 3] = [0, 0, 0, 1]
# Add translation
R_4x4[3, 0:3] = [cam.x, cam.y,
cam.z]

return R_4x4
```

Inputs:

- Camera position / angles in tanker reference system

Outputs:

- Transformation matrix from camera axis to tanker axis

4.1.5. Build transformation matrix from receiver axis to tanker axis

Compute the dot product between the input matrices.

Inputs:

- Transformation matrix from receiver axis to camera axis
- Transformation matrix from camera axis to tanker axis

Outputs:

- Transformation matrix from receiver axis to tanker axis

4.1.6. Get receiver angles in tanker reference system

The receiver angles in tanker reference system are calculated as the Euler angles from input matrix [6].

Inputs:

- Transformation matrix from receiver axis to tanker axis

Outputs:

- Receiver angles in tanker reference system

4.1.7. Get receiver position in tanker reference system

The receiver position in tanker reference system is calculated as the dot product between the receiver position in receiver axis ([0, 0, 0, 1]) and the input matrix.

Inputs:

- Receiver position in receiver axis
- Transformation matrix from receiver axis to tanker axis

Outputs:

- Receiver position in tanker reference system

4.1.8. Add receiver position/angles to the trajectory

The position/angle of the receiver in tanker reference system is added to the trajectory.

4.1.9. Project receiver marks

Once the position/angles of the receiver are calculated the receiver marks selected by the user in section 4.1 are projected in the camera image as blue circles (See Fig. 11). The projection error corresponds to the distance between the red and blue circles. This errors will be used to choose the best set of marks.

Fig. 11. Marks in blue automatically projected in the camera image.

4.2. Trajectory visualization

A visual review of the components of the trajectory is mandatory to detect failures in the reconstruction. The graphics are also useful to check the expected behaviour of the receiver (See Fig. 12-17). This step will iterate during the complete process in order to validate the final trajectory.

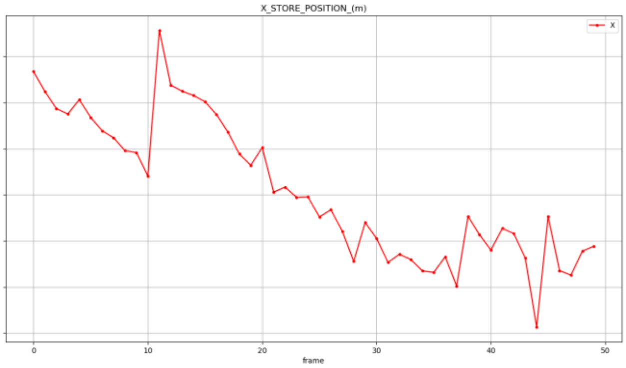

Fig. 12. X receiver relative position.

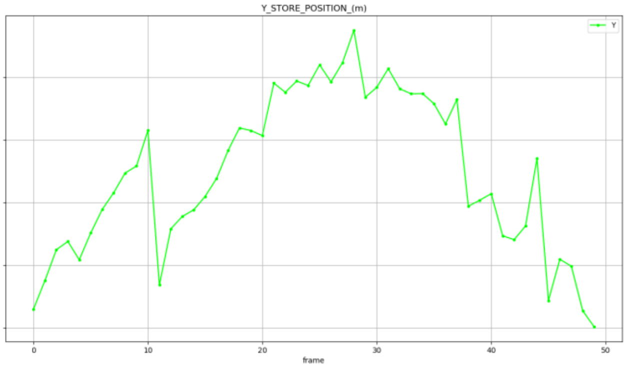

Fig. 13. Y receiver relative position.

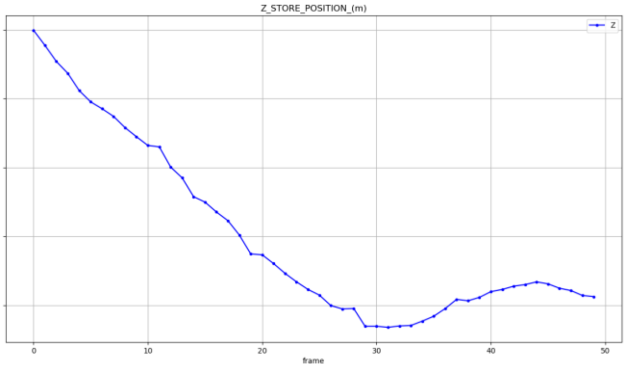

Fig. 14. Z receiver relative position.

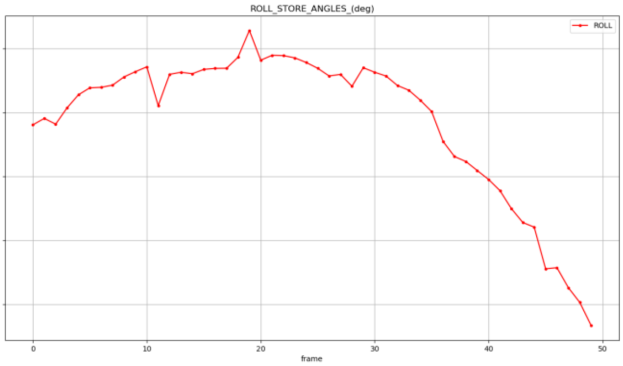

Fig. 15. Roll receiver relative angle.

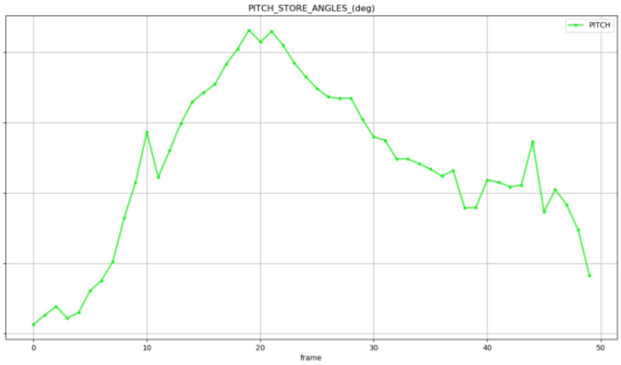

Fig. 16. Pitch receiver relative angle.

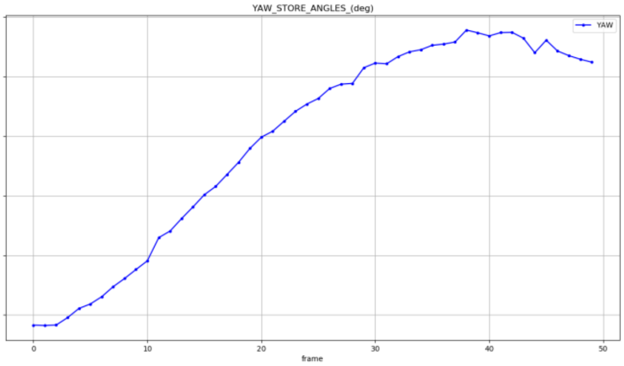

Fig 17. Yaw receiver relative angle.

4.3. Trajectory editing

In some cases the process detailed in section 4.1 generates wrong positions/angles of the receiver normally due to not enough accuracy in the marks receiver selection. In these cases there are two options:

a. Rework the marks in the receiver to gain in accuracy

b. Delete the position or angles of this frame and interpolate the hole with the information from the neighbors [7]

Option b is generally recommended when the hole is small.

4.4. Trajectory filtering

The trajectory calculated will be used to generate a relative speed to the tanker. The derivative process to calculate this speed will be more accurate if the trajectory is smoothed, therefore a filtering step [7] is highly recommended (See Fig. 18).

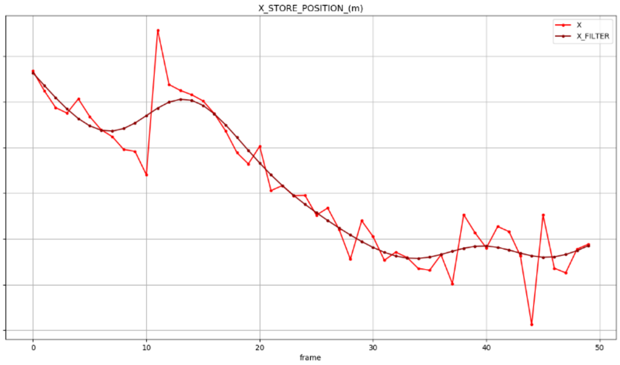

Fig. 18. X/X filtered receiver relative position.

4.5. Trajectory validation

A 3D bounding box with the dimensions of the helicopter is drawn in the camera image to validate the position and the angles of the receiver (See Fig. 19).

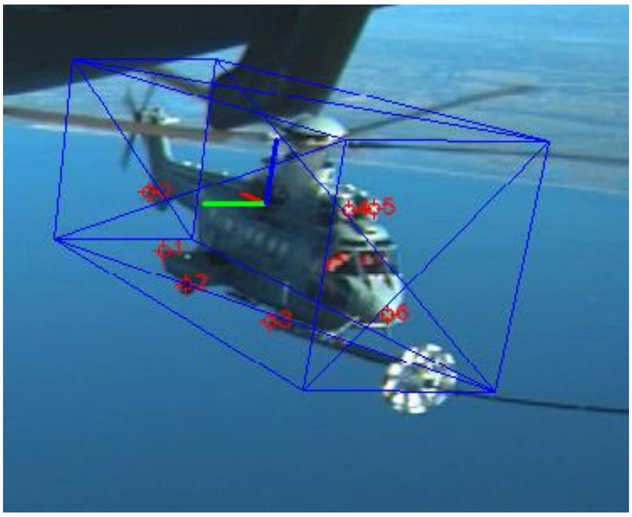

Fig. 19. 3D bounding box for validation.

These last steps could iterate several times until the trajectory is validated and sufficiently smoothed to produce a relative speed with the required accuracy.

4.6. Closure rate calculation

Once the relative trajectory of the receiver is obtained the closure rate can be calculated as a moving average speed of two elements in feet per second. In this step the three components of the speed and the speed absolute module are generated. A filter is applied to produce a smoothed speed (See Fig. 20).

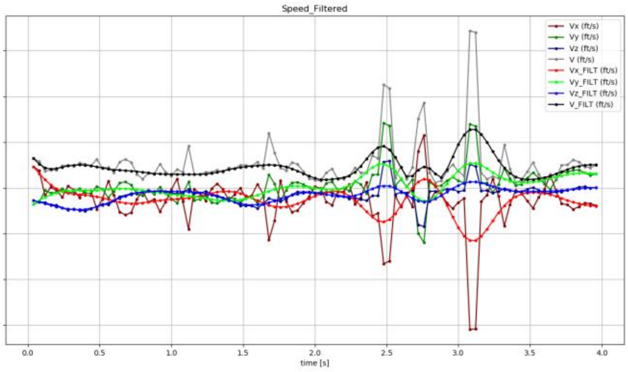

Fig. 20. Closure rate components and module. Raw and smoothed.

5. Methodology validation

The process explained in section 4 was applied to an artificial video generated by 3D Studio Max. The closure rate calculated with NEOS was validated against the theoretical speed used in the simulated video.

An empirical statistical accuracy study was done to check the error standard deviation in the generated trajectory respect to the theoretical one. The error factors considered in the study were:

- Error std in camera position / angles / calibration
- Error std in receiver marks selection

The error std in the closure rate was less than required, therefore the methodology was validated. One more time it was demonstrated that the simulation and a correct methodology were crucial for validation purposes.

6. NEOS vs other closure rate methodologies

6.1. Two cameras methodology

It is a method based on the tracking of just one mark using two cameras [1].

Advantages and disadvantages are presented with respect to the closure rate calculated using NEOS:

- Generates the 3D trajectory of one local point in the receiver meanwhile NEOS generates the relative position of the geometric center of the receiver
- Does not produce Euler angles
- Does not need to know the 3D positions of the selected mark in the receiver reference system
- Two camera positioning and calibration

6.2. One camera, 1-D methodology

It is a method based on the tracking of just one mark using one camera [2].

Advantages and disadvantages are presented with respect to the closure rate calculated using NEOS:

- Does not generate receiver trajectory
- Does not produce Euler angles
- Does not need to know the 3D positions of the selected mark in the receiver reference system
- Does not allow trajectory validation using the bounding box over the camera image
- Not camera positioning and calibration
- Not robust to lateral/vertical relative movements

7. Conclusions

This paper presents the methodology used for the closure rate calculation between the A400M and the helicopters. It also details the onboard camera installed in the tanker used for the photogrammetry algorithms.

The methodology is based on the safe separation internal tool to generate the receiver trajectory and angles in tanker reference system adding a last step to calculate the relative speed from this trajectory.

Virtual testing and empirical statistical accuracy study were used to validate the overall process.

Respect to other methodologies it is more complete and robust but on the other hand it needs information from the receiver model.

8. Acknowledgement

I would like to thank Francisca Coll Herrero for her support. I would also like to thank Moisés González Martín for giving me the opportunity to present this methodology.

9. References

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10. Glossary

AAR:	Air to Air Refuelling
FTI:	Flight Test Instrumentation
NEOS:	New Safe Separation tool
STD:	Standard Deviation