Synthetic Vision to Augment Sensor Based Vision for Remotely Piloted Vehicles

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ABSTRACT

In the past fifteen years, several research programs have demonstrated potential advantages of synthetic vision technology for manned aviation. More recently, some research programs have focused on integrating synthetic vision technology into control stations for remotely controlled aircraft. The contribution of synthetic vision can be divided into two categories. The depiction of the environment and all relevant constraints contributes to the pilot's situation awareness, while the depiction of the planned path and its constraints allows the pilot to control or monitor the aircraft with high precision. This paper starts with an overview of the potential opportunities provided by synthetic vision technology. A distinction is made between the presentation domain and the function domain. In the presentation domain, the benefits are obtained from making the invisible visible. In the function domain, benefits are obtained from the possibility to integrate data from the synthetic vision system into other functions. The paper continues with a number of examples of situation awareness support concepts which have been explored in the current research. After this, the potential contribution of synthetic vision technology to the manual control task is discussed and it is indicated how these potential advantages will be explored in the next research phase.

Keywords: Synthetic Vision Technology, UAV, RPV, Enhanced Manual Control.

1. INTRODUCTION

In a 2003 report[22] of the Scientific Advisory Board of the U.S. Air Force on the future of Unmanned Aerial Vehicles (UAVs) it is concluded that '*The Air Force needs to invest in mission management technologies. While flight control and basic vehicle technologies are already well developed, the technologies to actually manage the mission (such as automation, human-systems interface and dynamic replanning algorithms) are the key limiting factors to increasing both the performance of the UAVs and the vehicle-to-operator ratio. Although supporting work in mission management technologies was a recommendation of the 1996 SAB UAV Study, little work has been done in this area, and it remains a key area for focused investment'*. The challenge is the optimal integration of human and machine abilities to leverage the full potential of UAV capabilities.

Wickens[24] summarizes the advantages of having a human operator in the loop as: '*Humans can respond perceptually to a changing environment and to relations in the environment. They can go beyond the information immediately given, respond to low-probability occurrences, and adopt alternative strategies and alternative modes of performance when necessary. In short, humans are flexible*'. Without adequate displays, unique human capabilities such as the high degree of flexibility and adaptability, the possibility to recognize and exploit advantageous opportunities, and the possibility to integrate perceived data with other information to resolve ambiguities and detect contradictions, are not utilized.

Today's computer and display systems offer almost unlimited flexibility in the implementation of functionality and the presentation of data and finally allow the implementation of concepts which have been discussed for a long time but could not be implemented due to technical constraints. In a 2003 DoD study on reliability[4], Enhanced Synthetic Vision (ESV) technology is identified as a candidate to improve Situational Awareness (SA) and compensate for sensor limitations. The study presented here discusses the identified opportunities of synthetic vision technology to support the operators of both aircraft with and without the need for manual control[i].

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[i] Unmanned Aerial Vehicles requiring continuous manual control are typically denoted as Remotely Piloted Vehicles (RPVs).

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2. OPPORTUNITIES

2.1 Synthetic Vision

Although there is no single agreed upon definition of Synthetic Vision (SV), the common element in almost all definitions and implementations is a computer-generated depiction of the environment as seen from the cockpit based on spatial data. The basis for SV was established in the context of several military research projects, such as the Pictorial Format Program[23]. Although the term 'synthetic vision' was not coined yet, about twenty years ago extensive simulator evaluation was performed using displays that presented a computer-generated, spatially integrated depiction of the environment, the planned path and threat areas. The anticipated advantages that were pursued in this project comprised a reduction in radar signature made possible by a reduction in the use of active sensors and an increase in pilot SA because of the integration of information regarding threat areas.

With manned systems, SV is regarded as a means to increase SA[ii] and reduce the effects of limited visibility conditions. The commonality in information requirements between the navigation, guidance and control of manned and unmanned aircraft formed the basis for a feasibility study regarding the use of SV for UAV operator support[10]. As a result of this study, a research environment was realized for the development and evaluation of UAV operator station concepts. The key characteristics of the implemented SV concepts are the use of integrated data presentation to support the operator in obtaining level 2 SA and the immediate feedback on expected future effects of changes to the situation to support level 3 SA.

Based on results from our own research into synthetic vision[10-20] and a review of other research we have identified a significant number of opportunities in the visualization domain to support SA and in the function domain to provide operator support.

2.2 Presentation Domain

In the presentation domain, the use of SV enables:

- Visualization of the situation from another viewpoint than the sensor, for example a bird's eye view around ownship, thus providing better level 2 SA and supporting the build-up of level 3 SA[10].
- Augmentation of the sensor view. Examples are increasing the field of view, adding symbology to support *enhanced visual acquisition*, visualization of elements not (yet) available in the sensor image, and guidance augmentation. The basic idea is to support the anticipation of environment features and compensate for effects of sensor limitations such as field of view, effective range and occlusion (caused e.g., by clouds, precipitation, smoke or terrain)[18].
- Visualization of non-physical constraints[17], e.g., threat volume depiction.
- An intuitive means of distributed communication between geographically separated users[2].

2.3 Function Domain

In the function domain, SV data can be used to provide:

- Flight path de-confliction with terrain during planning[15].
- A predictive look-ahead terrain alerting capability to increase safety during off-path.
- Direct line of sight availability indication.
- Visibility prediction (from threats) to support path planning in order to minimize exposure[19].

Many of the SV enabled opportunities have been explored in manned aviation, sometimes for military applications, sometimes for commercial applications and sometimes for both. The examples provided in the following section describe already tested implementations that are expected to have direct merit for the operation of a UAV. In

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[ii] Endsley[3] defines Situation Awareness as: the perception of the elements in the environment within a volume of time and space (Level 1 SA), the comprehension of their meaning (Level 2 SA) and the projection of their status in the near future (Level 3 SA).

fact, all of the functions described in the examples have already been integrated into an experimental UAV operator station.

3. EXAMPLES

3.1 Visualization of the situation from another viewpoint

Any depiction of the environment based on a vehicle-mounted sensor is ego-centric by definition. In general, global spatial awareness improves with viewpoint exo-centricity, while navigational awareness for local guidance and control decreases correspondingly[7]. This means exo-centered viewpoints are best in presenting a strategic overview of the situation while (near-) ego-centered viewpoints provide more SA in the tactical and time-critical domain. The exo-centric perspective display shown in Figure 1 presents a vehicle-slaved point of view depicting the trajectory of the aircraft in the context of surrounding terrain and integrated with threat information.

3.2 Augmentation of the sensor view

Many options exist to integrate an Enhanced Vision System (EVS) sensor image into an SV scene. The 'best' way for integration depends on the tasks to be performed and the intended use of the resulting information by the operator(s). As a result, the optimal integration will depend on the intended function, the phase of the operation and the visibility conditions. For the payload operator, the larger available field of view (FOV) provided by SV and the use of geometric aids can support the spatial orientation and anticipation of the upcoming location of relevant elements that are not (yet) within the sensor FOV. Intelligence data on target and threat locations can be used to augment the sensor image with synthetic cues to provide *enhanced visual acquisition*.

Another opportunity comprises the use of an integrated depiction of the planned path to improve manual control[12]. Integrating the actual and the planned flight path into the sensor image supports the pilot in judging the integrity of the planned flight path and the current conformance to the planned flight path.. Figures 2 and 3 show examples of such an augmentation. In Figure 2, the pilot can determine that the future (database-derived) terrain following path is clear of the terrain, and in figure 3 the pilot can determine that the (synthetic) approach path provides guidance to a real runway.

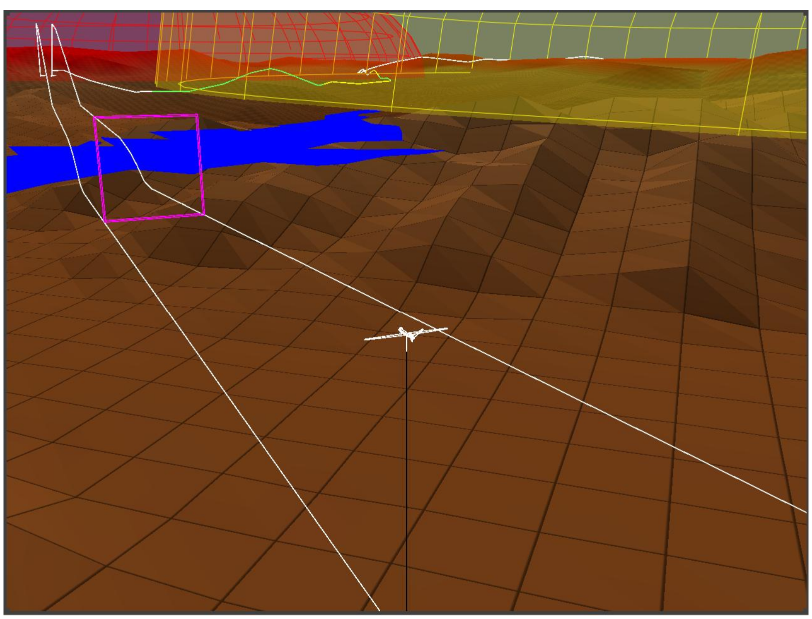

Figure 1: Exo-centric view of the UAV with terrain, threat envelopes and future Flight path.

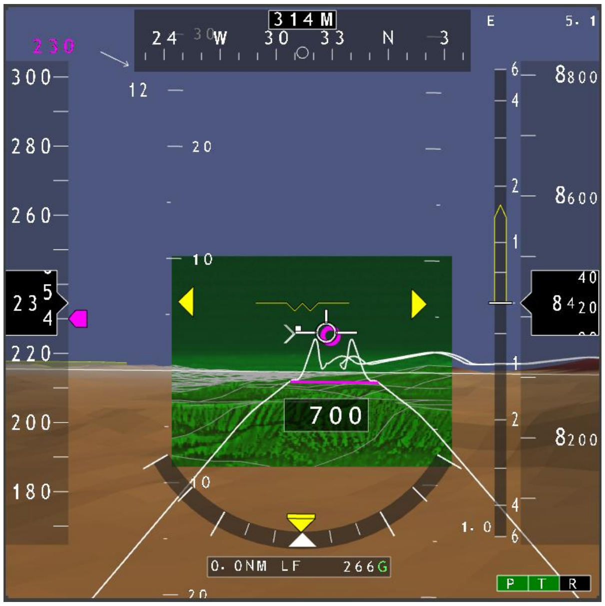

Figure 2: Example military SVS/EVS display format with integrated depiction of the future terrain following flight path.

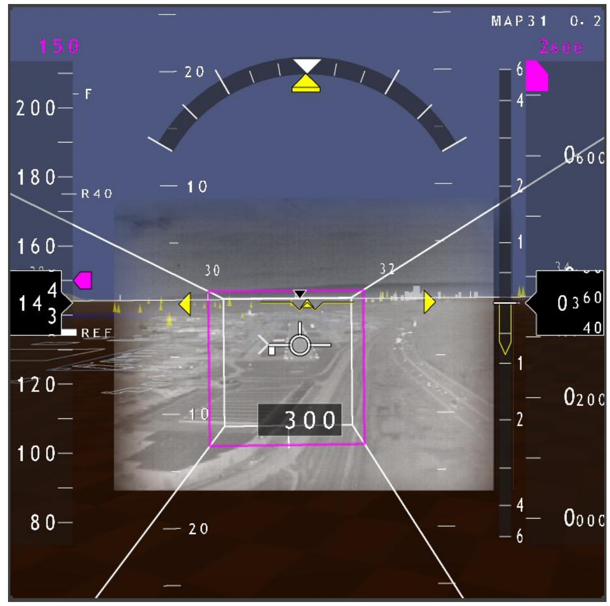

Figure 3: Example of a civil SVS/EVS display format with a flight path guiding the aircraft to a DH of 200ft.

3.3 Visualization of non-physical constraints

Given the fact that with SV terrain and obstacles are graphically represented in an ego–centered reference frame, whereas non-physical constraints (e.g., restricted airspace) are merely specified as text in a NOTAM, it is not unlikely that the accuracy of the location of the constraints in the pilot's mental spatial picture of the situation is less for these latter geospatial constraints. Similar to the spatially integrated presentation of physical constraints in SV systems through the depiction of 3-D volumetric objects, the non-physical constraints such as exclusionary airspace or threat lethality envelopes can also be presented through a depiction of their boundaries. This idea was already proposed in the context of the pictorial format program[23], in which volumetric objects in a perspective presentation of the aircraft environment represented areas of high lethality due to enemy SAM sites or AAA. In SV for commercial aviation the integration of information regarding special-use airspace into the guidance and the navigation displays has been used to increase the situation awareness of pilots during approaches in which they fly close to prohibited airspace. The concept was demonstrated in 2002 on board of the Boeing Technology Demonstrator during visual approaches into Reagan National Airport[21]. Figure 4 shows the Primary Flight Display (PFD) with the prohibited airspace above the White House, the Mall and the Capitol.

A military version of this prototype SV system was also developed. In this concept, threats are visualized through a depiction of the volume within which a high likelihood of successful engagement by the enemy defense system exists (Fig. 5). This concept was demonstrated between May 17 and June 9 2005 when 10 pilots evaluated an SVS with an integrated Terrain Following capability in the FAA William J Hughes Technical Center's Boeing 727-100 during actual test flights in New Mexico[20].

3.4 Flight path de-confliction with terrain

In the function domain, the availability of the terrain elevation database can be used to test for separation violations of the desired path in the planning phase. In case part of this path lies within a predefined limit from the terrain, this location can be identified, allowing these errors to be detected and corrected during the planning process.

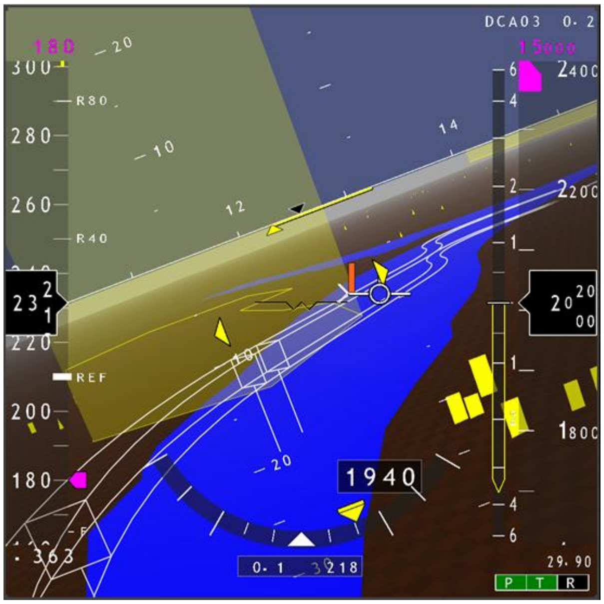

Figure 4: Example of a civil SVS format with integrated depiction of airspace constraints (yellow cylinders).

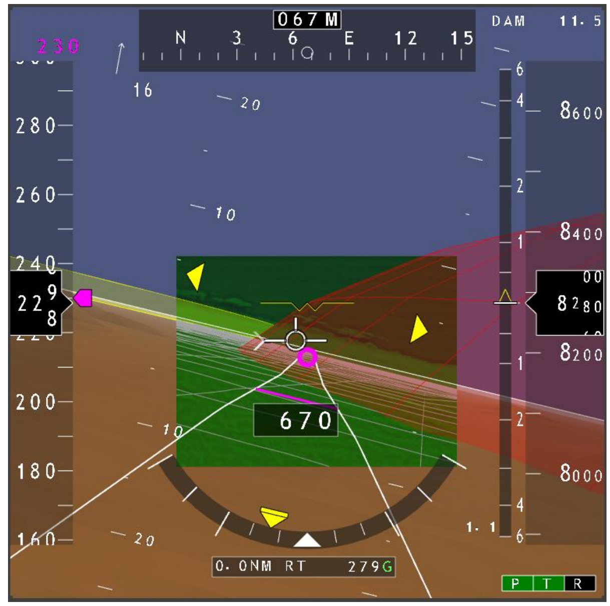

Figure 5: Example of a military SVS/EVS format with integrated depiction of threat data (red dome).

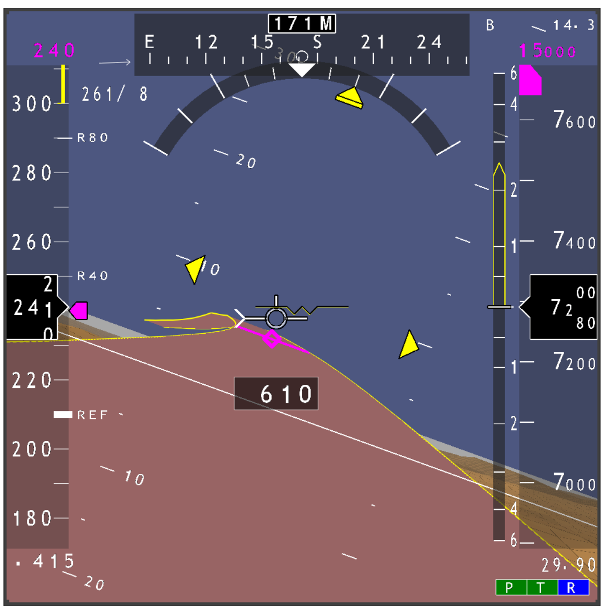

Figure 6: In case the UAV is within certain limits of the MSA floor, it changes from transparent to solid and a red hue is added.

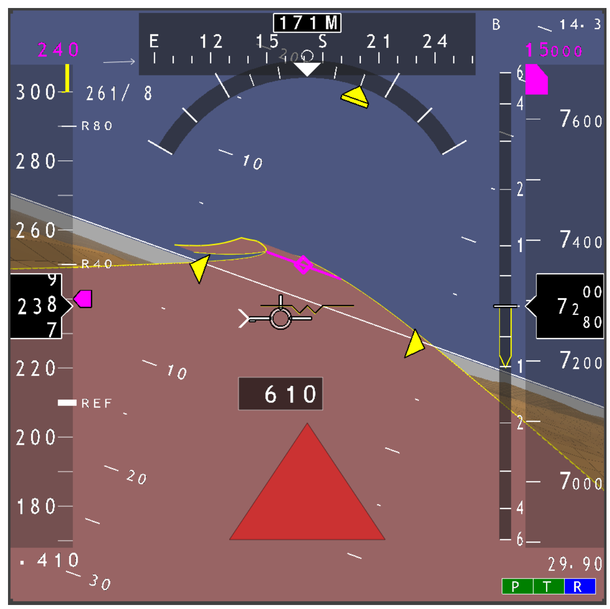

Figure 7: In case the location of the flight path vector indicates that the aircraft is about to cross the MSA, a pull-up cue is provided to the pilot.

3.5 Predictive look-ahead terrain alerting

In case the aircraft has to deviate from a conflict-free planned path, it is essential to have a timely warning for terrain separation violations. Using a prediction of the future path and a terrain elevation database, a test for the penetration of the Minimum Safety Altitude (MSA) can be performed. Such a database-derived predictive terrain separation monitor has been developed and integrated into an SV system for Terrain Following[20]. Figure 6 shows an example of the visualization of this concept. Based on an extrapolation of the current position, the future track of the UAV is computed.

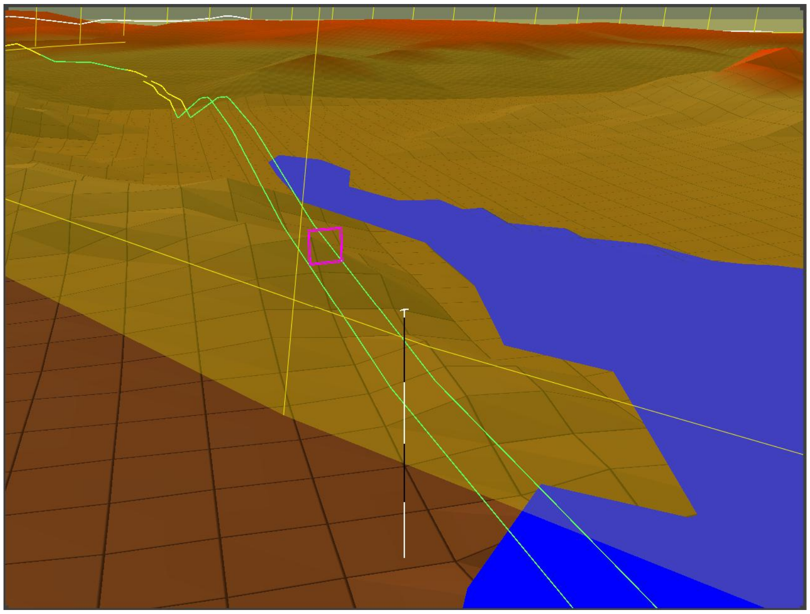

Figure 8: Example of the integration of threat visibility information in the depiction of the planned path. Along the green path the vehicle is masked by the terrain.

Along this track, the MSA is visualized by taking terrain elevation samples and adding the required separation (in this example 500 ft). In case the UAV is within certain limits of the MSA floor, it changes from transparent to solid and a red hue is added. Figure 7 depicts a situation in which the location of the flight path vector indicates that the aircraft is about to cross the MSA, and a pull-up cue is provided to the pilot.

3.6 Prediction of threat intervisibility

In case the mission objective requires the vehicle to navigate through an area covered by enemy systems, risk cannot be avoided. Typically, risk will not be the same at all geographic locations (e.g., due to terrain masking), hence the navigation plan can be designed to minimize risk by taking the information on known threats and the surrounding terrain into account. In Theunissen et al.[19], a concept is described that integrates the results from the threat intervisibility computations into the depiction of the planned path. Figure 8 illustrates this concept. The planned path crosses a volume within which the vehicle is in range of a weapon system. The green part of the path indicates the location where the vehicle is masked by the terrain and the yellow part indicates where the vehicle is visible providing the ability to anticipate situations where the UAV is vulnerable.

3.7 Research operator station

In the Netherlands, three UAV research operator stations have been created to support the joint research of the Royal Netherlands Naval College, Delft University of Technology and the Royal Netherlands Air Force. Figure 9 shows the research operator station located at the Royal Netherlands Naval College (department of the NLDA) in Den Helder. To demonstrate, evaluate and further explore the desired GCS functionality, the architecture of these research operator stations facilitate the seamless integration of new functions, while enhancements to the Human Machine Interface (HMI) are made using the methods discussed in Theunissen et al.[12,13].

3.8 Summary

The examples have illustrated the potential of SV technology to support a variety of functions, regardless whether the vehicle is manned or unmanned. One particular operational aspect that is different between manned and unmanned aviation is the use of the visual field information for manual control. Whereas in manned aviation the use of an imaging sensor is mostly foreseen as a means to increase integrity of an SV system, for all UAVs that are manually controlled, the imaging sensor provides an essential part of the information that is needed for a stable closure of the control loop. In the next section, SV enabled opportunities to support the pilot with the manual control task are discussed.

Figure 9: Research ground control station at NLDA.

4. ENHANCED MANUAL CONTROL

Within the scope of this study, manual control refers to the human operator's task of determining the commands to a dynamic system, -e.g., the UAV- to make its condition conform to a specified condition -typically a time-space trajectory- under influence of environmental uncertainties, preserving a stable feedback loop. Closed-loop stability is determined by system dynamics, and the feedback and control signals. In teleoperation, such as RPV control, the operator and system that has to be controlled are physically separated. As a consequence, the sensor feedback data from the system and the control actions from the operator are subjected to communication delays and limited update rates, adversely affecting closed-loop stability and thus hampering manual control.

Several potential contributions of SV technology to the RPV control task are foreseen. Probably the most significant contribution of SV is that it enables the integration of guidance information in a way that the operator can exercise control based on an understanding of the requirements. The next subsection explains how this can be achieved.

4.1 Physically interpretable error depiction

The integration of SV with the sensor image provides all new information into a single, ego-centered frame of reference. To support the operator with the manual control task, a conventional FD display is typically integrated into the sensor image. The FD provides the pilot with steering commands, but these commands do not convey any physically interpretable information and do not contribute to SA. An alternative to this concept is the visual integration of the future path constraints in such a way that, rather than following commands, the pilot controls the UAV based on an understanding of the path requirements. This concept has been extensively explored with SV for manned aircraft, and allows more precise control with lower workload and higher SA. It comprises two essential components: the depiction of the future path constraints to provide the preview needed for anticipatory control, and the integration of predictive information to compensate for the higher order system dynamics. The next two subsections describe these two components in more detail.

4.2 Path preview

In Section 2 SV technology was mentioned as a means of supporting path deconfliction in the planning domain. The planning domain typically refers to navigational, or outer-loop control and concerns planning of route waypoints and gross trajectory shapes[8]. Although seemingly not directly related to manual inner-loop control, the path preview function, i.e., the presentation of the future reference condition relative to all relevant constraints of the planning phase, can also be used for control action verification and (mission task) training purposes, thus indirectly supporting manual control tasks.

As exemplified in Subsection 3.2, in the actual inner-loop control domain the presentation of the planned path relative to the current vehicle condition enables the user not only to determine the current deviation from the path, but also to anticipate future required changes in position and orientation. This allows the operator to adopt more open-loop or anticipatory control strategies, reducing the effects of changes in the desired system state and allowing reduction of the required gain for closed-loop control[12]. Today's prototypes of SV displays for commercial aviation frequently include a perspective pathway representing the future planned path. Various studies have demonstrated the superiority of a well-designed perspective flight path display over an FD display in terms of increased tracking performance combined with a reduced workload. Similar advantages can be expected when using a perspective display for manual RPV control.

4.3 Output prediction

Delays in the feedback and control signals originate from data processing and transmission processes. Delays and limited update rates in the feedback control loop have adverse effects on the closed-loop stability margins. For vehicular control this is especially the case in the absence of any out-of-the window visual cues. Therefore delays and limited update rates are considered important factors impeding continuous manual control of UAVs. In general, an aircraft's robustness to delays in the feedback control loop is proportional to its stability margins, and inversely proportional to the bandwidth required for the control task[5].

SV enables the depiction of the aforementioned preview of the reference condition to be accompanied by the visualization of the prediction of the future state. This future state, or system output, is computed through extrapolation of current state and optionally taking into account expected future control signals.

In (space) telerobotics, output prediction is regarded as a means to suppress the decoupling between cause (operator control actions) and effect (system response), that is perceived by the operator when performing manual control tasks under time delay conditions[1,8,9]. In so-called predictive, or predictor display concepts the system dynamics are simulated without delay and the resulting simulated system state is graphically displayed immediately, presenting the operator the consequences of applied control actions in real time, before becoming visible in the sensor data. This gives the operator a qualitative confidence in the control action's consequences in the real world. Evidently, the synthetic environment provided by SV can be used for such a real-time feedback to the operator. However, this can not exactly be accomplished in a single ego-centric reference frame with sensor augmentation, since sensor and synthetic data are, in that case, no longer synchronous.

Another approach is to augment the synthetic ego-centric perspective display that is synchronized to the senor data -and thus delayed- with predictive guidance symbology, rather than simulating and presenting the entire ego-centric synthetic environment for the actual (non-delayed) or future state. Figure 10 exemplifies the use of predictor symbology in a sensor-synchronized reference frame (i.e. relative to $t=t_0-t_d$); depicted are the predictor symbols for the simulated real-time position ($t=t_0$) and the simulated position after a certain predictive time-span ($t=t_0+t_p$). To avoid ambiguities in the perspective presentation, SV can provide cues that relate the position of the predictor symbol to a location on the actual or planned perspective flight path. The potential of predictive symbology to support the tracking of higher-order systems[24] and compensate for the limited visual field cues[5] has been recognized; the feasibility of these concepts was demonstrated but never implemented in an RPV control station.

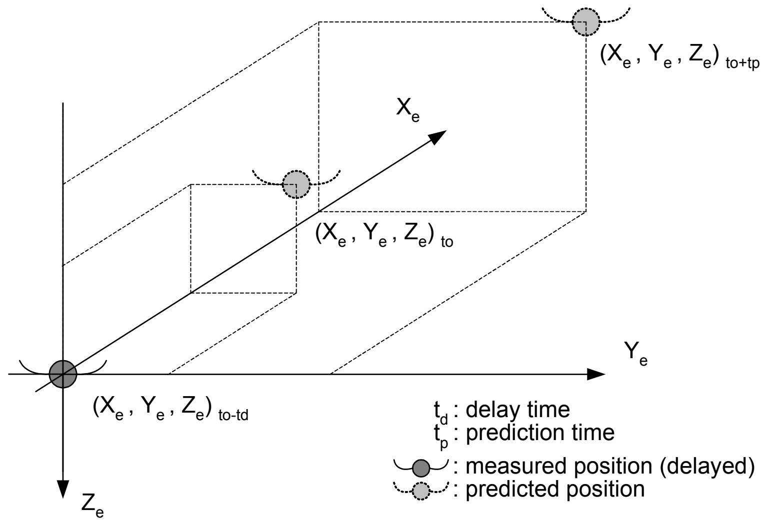

Figure 10: Predictive symbology in a sensor-synchronized ($t=t_0-t_d$) ego-centric reference frame

4.4 Future Work

It is expected that the manual control of a UAV can be significantly improved by using an SV compatible guidance concept. This should translate into lower training cost and a fewer manual control related accidents. To explore the potential of SV in achieving this goal, an experiment is being prepared. This experiment will focus on exploring the ability of trajectory preview and candidate predictive guidance symbology (augmentation manner, predictive span) to compensate for the effects of delays typical of UAV operations, both within line of sight (LOS) control range and beyond. Representative tasks to be evaluated are: flying curved landing approaches (within LOS) and precision maneuvering over target areas (beyond LOS).

5. SUMMARY

The major difference between navigation, guidance and control of manned and unmanned aircraft is that in manned aircraft enhanced display technology is used as an addition to the out-of-the window view, while in unmanned aircraft the presented data is the sole means for building-up SA and determining control actions. The information presented to the operator of an unmanned vehicle typically originates from a limited FOV camera. Furthermore the sensor data from the system and the control signals from the operator are subjected to additional delays and limited update rates.

An overview was presented of opportunities that the use of SV technology introduces for providing support to the operators of UAVs, by increasing SA, reducing the effects of limited visibility conditions and compensating for the undesirable consequences of teleoperation. Due to the commonality in information requirements of manned and unmanned flight, much of the functionality potentially beneficial for UAV operator support could be adapted from functionality demonstrated in existing manned aircraft research systems. In exploring the opportunities of SV, a distinction is made between the presentation domain and the function domain. In the presentation domain, the benefits are obtained from making the invisible visible. In the function domain, benefits are obtained from the possibility to integrate data from the synthetic vision system into other functions. Additionally, the potential contribution of synthetic vision technology to the manual control task has been addressed. The identified operator functions have been integrated into a research ground control station and will be evaluated in experiments in the context of further research.

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