TACOM - AIR-LAUNCHED MULTI-ROLE UAV

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Abstract

This paper describes the development of TACOM (Multi-role small UAV, TAyouto K(C)Ogata Mujinki in Japanese). It is intended to demonstrate an air-launched UAV focusing on key technologies to establish a small high-speed UAV system for multiple missions. The key technologies to demonstrate are high speed stealthy configuration, wing expansion, GPS/ADS (Air Data System) hybrid navigation, and autonomous target tracking. The TACOM system consists of UAVs, Ground Control Stations (GCS), Ground Support Equipment (GSE) and carrier aircraft conversion kits. The UAV is equipped with an InfraRed (IR) sensor that downlinks images to the GCS in real time. Technical Research and Development Institute (TRDI) of Japan Defense Agency (JDA) started the TACOM program in 1995 with the prime contractor, Fuji Heavy Industries (FHI). TRDI and Japan Air Self Defense Force (JASDF) completed its evaluation flight test in 2001 with successful demonstrations of the key technologies.

1 Introduction

Penetrator UAVs have been in service for various nations' militaries accounting for their advantages that they are low-observable and hard to shoot due to their high speeds. For example, Bombardier's CL-289 for German and French forces, Finmeccanica's Mirach 150 for Italian Army, Tupolev's VR-2 Strizh and VR-3 Reis for Russian and former USSR nations' forces have been developed for strategic reconnaissance missions. In particular, the derivatives of Ryan Aeronautical's (currently Northrop Grumman) BQM-34A Firebee aerial target for U.S. forces used in Vietnam War era are one of the historic UAVs that had proved UAVs' significant contributions to military operations. In fact, some of the derivatives are featured by air-launched deployments.

On the other hand, JDA started the license production of BQM-34A Firebee aerial target for Japan Maritime Self Defense Force under the contract with FHI from 1970. In addition, JDA has a history of indigenous UAV developments. TRDI and FHI successfully developed the first indigenous air-launched aerial target called J/AQM-1 Target Drone for JASDF in 1987. Near the end of the J/AQM-1 development program, they started a conceptual study on a high-speed reconnaissance UAV and preliminary researches on a long-range data link, a stealthy aerodynamic configuration, etc. As for rotorcraft UAVs, they also successfully developed a system called FFOS [1,2,3] for Japan Ground Self Defense Force between 1991 and 1996. The system was, in fact, believed to become one of the first rotorcraft UAV systems fully operational for target acquisitions and damage assessments in military service in the world. Following the conceptual and preliminary studies and the experience of the UAV system integration for FFOS, TRDI started the TACOM program which is intended to demonstrate key technologies to establish an air-launched multi-role UAV system based on the requirement by JASDF in 1995. FHI was again awarded the contract of the TACOM design and manufacturing program between 1995 and 1998. The TACOM was then delivered to TRDI and evaluated in the engineering ground and flight tests between 1997 and 2001.

Although the requirement did not specifically assign the mission of the TACOM, possible missions for it are considered to be surveillance, reconnaissance, aerial target, decoy, electric warfare, experimental test bed, etc. Whatever the mission is, some technical challenges must have been overcome to go for the development of an operational air-launched multi-role UAV system. Therefore, this program, as a demonstration program, focused on four technologies to demonstrate as follows:

- High-speed stealthy configuration
- Wing expansion
- GPS/ADS hybrid navigation
- Autonomous target tracking

As mentioned, high-speed penetrator UAVs, or UAVs in general, are playing more important role than ever in military operations for mainly the reason that UAVs can collect information in highly threatened area where men cannot reach. However, the completions of the UAV missions would be still threatened by fighters, Surface-to Air Missile (SAM) batteries or man-portable SAMs. It is, therefore, still better for the UAV to be less detectable, i.e., simply smaller, faster and stealthier. The program, thus, pursue a high-speed stealthy configuration.

In order to extend the operational range of such a small UAV, carrying the UAV by another airplane to a close range of its operational area might be expected. However, a UAV with an extended wing would be too large for a small carrier airplane, e.g., fighter, to carry especially when it carried external fuel tanks or other stores. A foldable wing would be a solution proposed in the program for the TACOM, but the control of the separation and wing expansion would be complicated and challenging.

These small UAVs should not be expensive, but should still accurately be guided and navigated for accurate target detections. Recent GPS accuracy would help construct a simple navigation system without an expensive inertial measuring unit. A dead reckoning with periodical GPS position references was examined in the program, being named the GPS/ADS hybrid navigation system.

The last key technology came up with a specific mission. Collecting the images of targets is the most important part of missions for recent UAVs. But, in reality, that is not easy for UAV operators on the ground because the target may not be stationary, but moving. Therefore, an integrated control of a platform and a sensor along with an instant method of creating a UAV orbit to track the target autonomously would be necessary. An autonomous target tracking named Target Management System (TMS) was developed and examined for the TACOM in the program. It can be done by just clicking a target on the screen that shows sensor images.

2 Demonstration Concept

The TACOM would be deployed in various scenarios. Watching invading guerillas on islands or the homeland might be one of them. The program picked a scenario in which the UAV surveys an unknown boat such as a suspected spy boat as illustrated in the Figure 1. The demonstration was then conducted in one of the JDA's training area over the sea for safety.

As mentioned, the UAV is carried by aircraft from a base. A JASDF's fighter, F-4EJ was used as the carrier aircraft in this demonstration program. Therefore, the UAV's dimensions are determined so that the F-4EJ can store two UAVs with their wings folded and three external fuel tanks simultaneously under the F-4EJ's wing. The UAV is then launched in

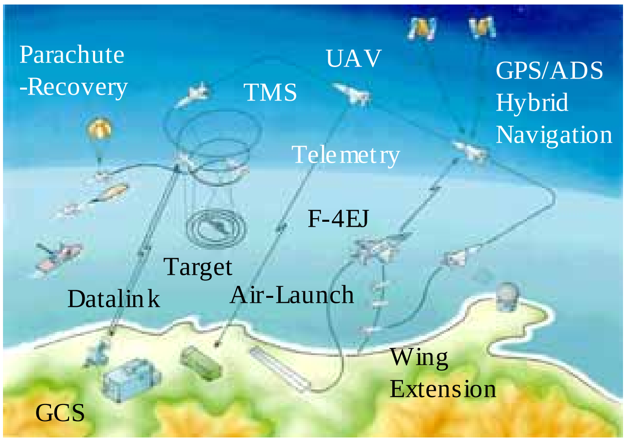

Fig. 1. Demonstration Concept

the area with its engine started prior to the launch and spreads the wing and establishes its attitude as soon as it is separated. Although not demonstrated, a rocket-assisted take-off from the ground was considered in the structural design.

Once it is launched, it is navigated using positions determined by the combination of GPS and either an Attitude and Heading Reference System (AHRS) or an ADS, such as Pitot-static probes. It may proceed with the maximum cruise speed to the area over the likely target passing the allowable spaces around the waypoints one by one.

The UAV is equipped with an IR sensor to detect and identify targets. Imagery obtained by the sensor during the flight would be transmitted via data link to the GCS. Once it finds a target on the sea, an operator in the GCS can engage TMS which makes an optimum spiral orbit of the UAV to approach the target for better resolution images. For TMS, there are two modes of target tracking. One is to keep a fixed point on the surface at the center of the sensor image, and the other is to keep the target at the center of the image during the orbit to provide target images consistently.

Toward the end of a mission, the UAV proceeds to the recovery area where a recovery boat waits for it. It then deploys parachutes and air bags for soft landing on the sea. The boat approaches to the UAV to pick it up and complete the mission. A land recovery would be also possible with the current recovery system.

During the mission, command and control are performed through radio frequency Line Of Sight (LOS) datalink between the UAV and GCS. Sensor imagery is also downlinked to the GCS in a real time fashion. In addition, the F-4EJ can command an emergency recovery or a flight termination for fatal conditions.

3 Program Schedule

As previously described, TRDI started the TACOM program based on the requirement by JASDF in 1995. In the contract of the program, FHI designed the system and built six UAVs, GCS, GSE and the F-4EJ conversion kits. They also conducted wind tunnel tests, Radar Cross Section (RCS) tests, structural tests, hardware-in-the-loop simulations, and integrated functional tests using the real UAV and GCS. Mitsubishi Heavy Industries was the other contractor to design and build the F-4EJ conversion kits to carry and command the UAV for the program.

Following the contract, the TACOM was delivered to TRDI and evaluated in the engineering ground and flight tests between 1997 and 2001 conducted by TRDI with a support by JASDF. The ground test included mechanical and electrical checks, ground vibration test and recovery test. In the flight test program, the F-4EJ compatibilities and captive flight tests (CFT) were performed as well as the evaluation of the four key technologies. The first fully autonomous UAV flight took place on May 7, 1999. The system has finally accumulated 22 F-4EJ flights including 5 independent UAV flights.

The TACOM evaluation program was completed in 2001 with satisfactory results. Based on this experience, JDA has just started the follow-on UAV program in 2004.

4 System Overview

The TACOM experimental system consists of six UAVs, GCS, GSE and the carrier aircraft conversion kits. Descriptions on the main feature of each component are given in more detail in the following subsections.

4.1 UAV

The UAV is featured by a high-speed low-observable aerodynamic shape with a sharp nose and a delta wing. The fuselage is 4.7m in length and 2.5m in width. It weighs 619kg at launch. Teledyne Model 382-10J turbofan is selected as the engine because it generates enough thrust for a high-speed penetrating reconnaissance. Compatibility with the F-4EJ determined the dimensions of the UAV and required that the UAV wings could be folded as mentioned. Since it has foldable wings in which there is little space for control surfaces, the UAV is controlled with only horizontal and vertical tail wings rather than having control surfaces on the foldable wings. The UAV also has ventral fins to contribute lateral and directional stability

As far as the stealth is concerned, edge management is considered for the reduction of RCS. In addition, a curved intake duct is routed from the upper fuselage to the engine to prevent radar reflections against lower possible threat directions.

The subsystem layout is given in Figure 2. Mission Management Computer (MMC), installed in the forward fuselage, commands actuators, datalink antennas, an IR sensor and other instruments based on flight status, datalink commands and sensor information. Two directional data link antennas and an omnidirectional antenna are mounted providing command and control or imagery transmission within LOS. An IR sensor is mounted inside the front fuselage. The sensor is controlled and stabilized by two-axes gimbals. In order to look down the targets during turns, the sensor rotates about the roll axis and the sensor windows are located more than a half lower surface of the fuselage to keep the field of view. For the wing expansion, irreversible actuators are installed in the inboard wings. Finally, parachutes as aerodynamic decelerators and air bags as shock absorbers for recovery are located so that they do not interfere with the other devices while they operate.

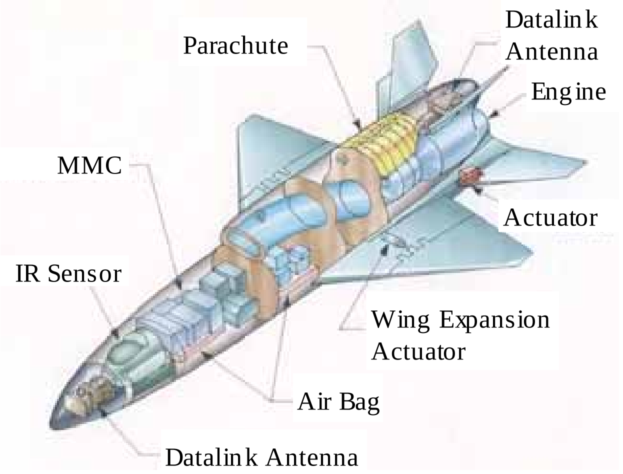

Fig. 2. TACOM Subsystem Layout

The system continuously monitors the health and status of the UAV and its subsystems. In the event of a flight critical failure such as equipment malfunctions, loss of communications, etc., the system will invoke autonomous contingency procedure and alert the operators. A flight termination could be commanded autonomously or intentionally by the operator in the GCS or the F-4EJ in case of a fatal situation.

In order to verify the system with a gradual step-up minimizing the risk of losing UAVs, the TACOM experimental system includes five different types of UAVs depending on the purpose of the tests. Type I is only an airframe with its wing fixed in the folded position for the verification of a safe separation. Instruments are added to Type II to measure separation trajectories, attitudes and loads. In Type III, MMC, wing expansion actuators, a parachute and air bags are added. Although Type III is a non-powered airplane, it is completely pre-programmed to perform an air-launch, glide and a recovery, which are fundamental functions for a reusable vehicle. Type IV additionally has an engine and datalink sets that enable MMC to perform fully autonomous flights without sensor operations. Type V equipped with a sensor for full mission demonstrations.

4.2 Ground Control Station

The GCS is comprised by a shelter that contains workstations for controls and commands of the UAV and a directional antenna that searches and tracks the UAV via LOS datalink. The GCS monitors the UAV flight information, system health and status throughout the mission and receives imagery data downlinked from the UAV in real time.

The UAV flies autonomously in compliance with a mission plan. The mission plan basically gives way points defined as longitude, latitude and altitude. A mission planning is also possible on the control and command workstation in the shelter. Using the GCS, an operator can input way points and an observation point to create a flight path of the

Fig. 3. Ground Stations

UAV in advance, which is automatically calculated taking care of the datalink. The mission plan is then loaded into the UAV using the GSE.

It also contains an image processing workstation. The real time sensor image is shown on the monitor of the workstation for sensor controls in the GCS. A sensor operator controls the sensor with an input device to find a target.

4.3 Carrier Aircraft Equipment

It consists of cockpit panels, an interface computer and cables. In the F-4EJ, the cockpit panels are added with which a pilot can turn on the power of the UAV, start Built-In-Test, ignite or stop the UAV engine, command an emergency recovery or a termination.

4.4 Ground Support Equipment

The GSE consists of avionics checkers, datalink checkers, an engine run station and maintenance kits.

5 Evaluation Flight Test

The evaluation test of the TACOM experimental system consists of some ground and flight tests. The UAV was launched, flew and dropped within a limited range of a JDA’s training airspace over the Sea of Japan. The GCS was placed in a JASDF Air Base which is located at the coast of the Sea of Japan. The recovery boat departed from and returned to a port which is also located at the coast. A sensor target barge was anchored in the range.

In the ground tests, loading procedures were at first established with fit trials. Required clearances were kept in the fit trials in which the three tanks and two UAVs were loaded. Then, flutter analysis with the elastic modes measured in the ground vibration test showed that the F-4EJ carrying the UAV had sufficient flutter margin within the operational flight envelope. The ground functional check was conducted to verify that no electromagnetic interference was realized among the F-4EJ, UAV and GCS. The UAV was also verified on the ground to function under circumstances in which the F-4EJ radar pointed it. Recovery rehearsals were finally performed to establish the procedure.

F-4EJ flight tests carrying the UAV were carried out for a couple of configurations to verify performance, flying qualities, flutters and flight loads. The flight loads acting on the UAV were also collected during the flights. The flight envelope was expanded through the flight tests with sufficient margins in terms of flutter, loads and stability.

Prior to the maiden UAV flight, flight test sequences including the engine starts and the sensor image transfer were tried in CFT using the F-4EJ carrying the UAV datalinked with the GCS. The engine started to idle within an

Fig. 4. F-4EJ carrying TACOM

Fig. 5. TACOM in Flight

intended period at the preferred flight condition at which the altitude test of the engine showed almost the same start characteristics. The sensor control for TMS described later in Section 5.4 worked correctly to track the target on the sea. Total of 15 flights were used for the compatibility test and CFT.

For UAV flights, two non-powered separation flights using Type I and II were taken. In addition, total of five autonomous UAV flights were carried out using Type III, IV and V in the evaluation flight test program, through which flight performance, pre-programmed flight, air-launch, wing expansion, parachute recovery, overridden commands, emergency procedures, target tracking functions, etc. were verified resulting in satisfactory agreements with pre-flight simulations.

During the evaluation flight test, data concerning the flight performance and the functions of the UAV was collected. In addition to the information downlinked to the GCS, data collected by flight instruments on the UAV was received through telemetry by another ground station for monitoring and gathering data. Vibrations at some representative points on the UAV were also measured and recorded on tapes.

The following results describe the parts of demonstration with how the four key technologies were demonstrated.

5.1 Wing Expansion and Recovery

The separation was carefully established using a couple of UAV types. Type I and II, simply ejected from the F-4EJ in respectively different flight conditions, showed almost straight trajectories without abrupt nose-up or climb. Type III, no engine version of the UAV, was then the first model to perform successful wing expansion during the separation. In normal procedure illustrated in Figure 6, the UAV starts controlling its roll 0.3 second after the separation and the pitch control follows that 1.5 seconds after the separation. The wings are then extended by actuators 3.0 seconds after the separation. The UAV pulled up its nose as soon as the wing expansion was completed to establish a level flight and hold its attitude and altitude for a second as shown in Figure 7. No exceed of altitude loss, attitude change and load factor than designed values were observed in the flight test.

In the actual procedure, the UAV engine must be started prior to the separation. Fully equipped Type IV and V eventually made successful separations with this procedure as expected by simulations as well as Type III.

The recovery sequence was also demonstrated using Type III, IV and V. When the recovery is commanded, a power off climb decelerates the UAV to be ready for a parachute deployment. The parachute drops the UAV to a certain altitude where air bags are deployed. During the flight test program, the recovery sequence worked as designed without an irreparable damage on the major structure of the airframe in spite of unexpected swinging motion

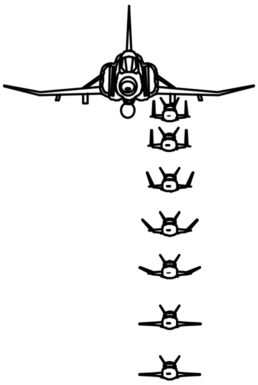

Fig. 6. Separation & Wing Expansion

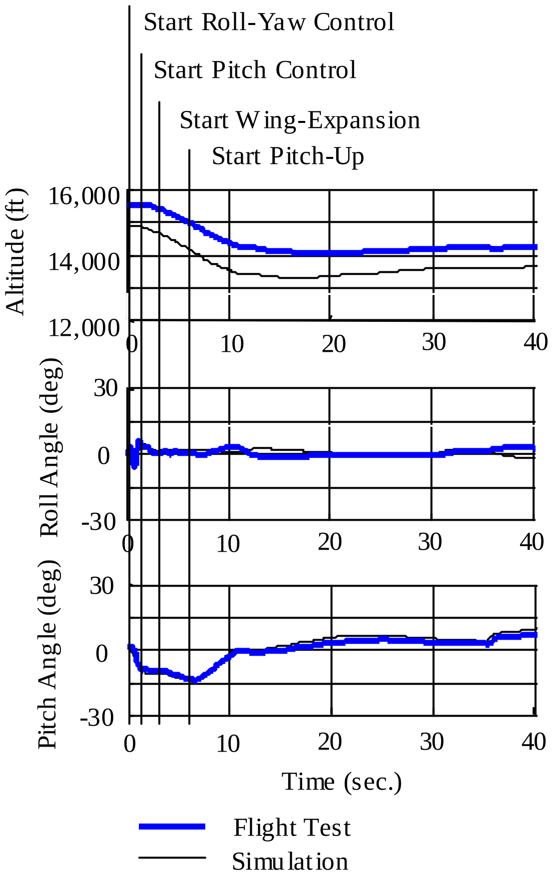

Fig. 7. Separation Trajectory

through the recovery. The airframe was washed and able to be reused for the later flights.

5.2 High-Speed Stealthy Aerodynamic Design

During the evaluation flight test, data concerning the flight performance of the UAV was collected. The flight performance is sometimes hard to demonstrate due to the difference between design conditions and actual flight and aircraft conditions in flight tests. Therefore, some performances were estimated using excess thrust calculations given by the operating conditions such as engine rotation speed, altitude, temperature, etc. As a result, the required maximum speed, service ceiling and turn rate were supposed to be met as well as the required maximum endurance. The aerodynamic performance of the stealthy configuration was thus proved to be sufficient.

Fig. 8. Recovery

5.3 GPS/ADS Hybrid Navigation

The UAV positions for the pre-programmed navigation are determined by either the GPS/AHRS or GPS/ADS hybrid navigation. For the GPS/ADS navigation, continuous ADS velocity integrations were regularly referred to discrete GPS positions to eliminate the position errors due to wind velocities as much as possible and provide continuously accurate UAV positions. In the flight tests, starting from the GPS/AHRS, the UAV engaged the GPS/ADS during a straight level flight and turned it back to GPS/AHRS as shown in Figure 9. Both navigation mode provided UAV with continuous outputs for positioning which enabled UAV to position a target on the ground

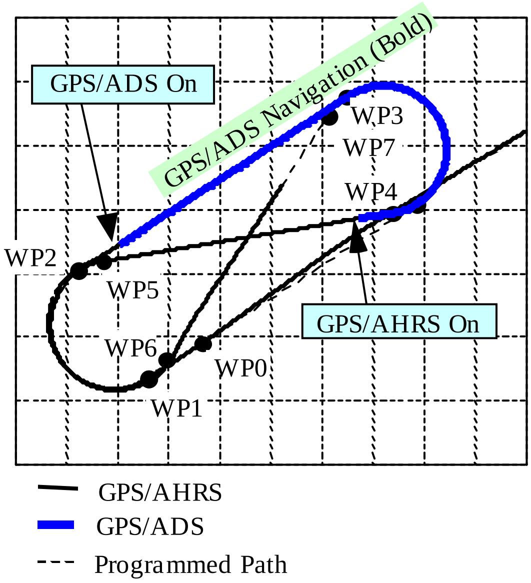

Fig. 9. GPS/ADS Trajectory

accurately. In fact, the GPS/ADS navigation made almost no difference from the GPS/AHRS navigation except for slight bank angles at turn.

5.4 Autonomous Target Tracking

The TACOM is able to fly around a target to take its image continuously. To accomplish this, UAV keeps a target at the center of the sensor image while it approaches to it with a spiral orbit as shown in Figure 10. For the target tracking mode, one of the two tracking modes, the orbit is created so that the relative distance between the UAV and the target decreases while the target moves.

The sensor image taken in the flight test kept the target within about 2% area of the whole image around the center. The actual flight orbit in Figure 11 shows the UAV traced the orbit as intended. As soon as the TMS is engaged, the UAV starts almost a 360 degrees turn to transit to the TMS orbit for target tracking. To resume the programmed orbit, the UAV made another transition turn to adjust the turn radius.

6 Conclusion

Through the entire program, i.e. design, fabrications and evaluations, all the technical goals related to an air-launched multi-role UAV were successfully demonstrated. These technologies were evaluated to be ready for the development of an operational system

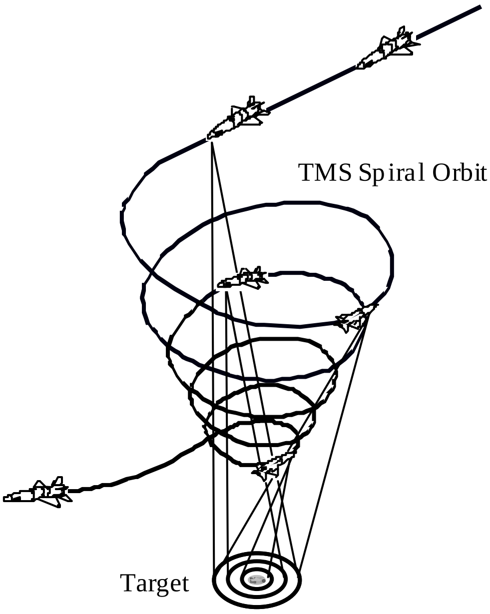

Fig. 10. TMS

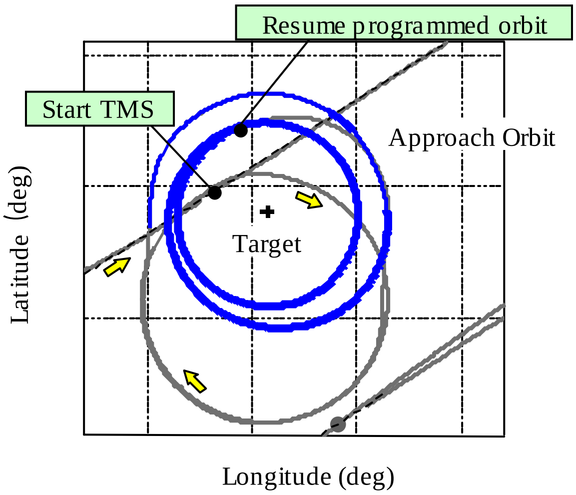

Fig. 11. TMS Trajectory

7 Acknowledgement

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