Case F: Fighter Avionics System Design

For want of a nail, the shoe was lost;
For want of shoe the horse was lost;
For want of a horse, the rider was lost;
And for want of a CONOPS, the battle was lost.

With apologies to Benjamin Franklin,
1706–1790

The Problem Space

It is the late 1960s. The Cold War is in vogue. Mutually assured destruction (MAD) is the political philosophy of the day. The nation faces an ever-present threat of air attack and must defend itself against the enemy who, Intelligence reports, has the potential to attack in force at high and low altitudes, using a variety of weapons, including nuclear bombs . . . parity must be maintained.

However, it is all very expensive. So, instead of weapon systems aimed at specific targets and specific enemy vulnerabilities, perhaps it may be possible to be a bit smarter and produce airborne weapon systems that can undertake a variety of roles, such as interdiction and strike, counter-air, ground attack, reconnaissance, etc.

A conceptual solution is mooted in which a new aircraft will be designed primarily to undertake the low-level ground attack role. With the addition of suitable sensing and photographic equipments, the same aircraft should be able to undertake reconnaissance missions, and with suitable radar, it should be able to detect and engage targets at sea and ashore. So, the conceptual solution is a multi-role aircraft for operation against enemy targets at low level, over land and sea.

Perhaps the same aircraft can be adapted for use as an air defense fighter-interceptor? Now that really would save money . . . .

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Prescribed Solution

So, (the defense department of) government established a requirement for an air defense variant of the multi-role aircraft. Government already had in development advanced interceptor radar with many of the features that would be needed by this new variant. Government also had a new, semi-active homing air-to-air missile that would work with their new radar. Good planning, it seemed, had set the stage for a swift, economic and successful development of the new, air defense variant of the multi-role aircraft.

To ensure that its production costs were kept in check, government decreed that the air defense variant was to use 80% of the equipments and facilities already designed for, and being fitted to, the other variants. This certainly made sense economically, and seemed to make sense in systems terms: the two-man crew could use the same controls and displays, perhaps with different legends; most of the sensors would be the same, for altitude, attitude, airspeed, mach number, etc., etc; wings, engines, powered flying controls, etc. — surely, none of these need to be changed.

So, the stage was set for a truly cost-effective, new air defense fighter. All that was needed now was to engage a group of designers to integrate the new radar and the new missile with the aircraft and systems already on the multi-role aircraft.

Except . . . the new radar and the new missile were being developed under fixed-price government contracts, within which there were no allowances for the developers to communicate, let alone cooperate, with anyone wishing to integrate their advanced technological artifacts. So, they would not be talking to the aircraft designers and system integrators — not, that is, unless a large amount of money was made available and not unless government accepted that, in consequence, both the radar and missile programs could be delayed. As it transpired, the radar would experience development problems extending over many years in any event . . . .

Designing the Solution System

Blissfully unaware of such difficulties, the system design team assembled, and organized along the lines shown in 'Organization for applying the systems methodology and for systems engineering' on page 304. The avionics system design, test and integration contract had been awarded, not as expected to the aircraft manufacturer, but to a systems house: this mirrored, in part, what had happened to the original multi-role aircraft. The aircraft manufacturer was not pleased: they immediately formed a system design team of their own to 'shadow' the systems house team man for man. No design meetings could be held, no decisions could be made, they declared, without their corresponding team members being present . . . not too happy, then, and determined to recapture their self-declared, former preeminence as systems designers.

Flies in the ointment

The first problem facing the assembling systems design team was getting information. To understand their design and integration task, they needed to gain information about all the many and various systems and subsystem that were to be pulled together into the avionics suite for a modern air defense fighter. That was a long list. There were the usual instruments, of course, an automatic flight control system, a defensive aids suite, a new head up display (HUD), the new missile, and of course the new radar. There were secondary radar identification systems, short-range air-to-air self-defense missiles, and even a proposed night visual identification system.

The design of this Night-Visident System, and even the way it was to operate, were to be determined. Its purpose was to enable visual identification by the crew of intruder aircraft, so that they could be warned off, or even engaged, but only once the interceptor crew were satisfied as to their true identify — shooting down the wrong aircraft during the Cold War could prove 'regrettable.' But, how to illuminate the intruder without blinding the crew — neither a searchlight nor a simple flashgun device would do . . . perhaps some short wavelength radar? Clearly, this was a research problem, not a systems design issue.

Many of the new subsystems that would be form part of the AD variant avionics system existed as self-contained systems. There were weapons management subsystems that were designed to interface with equipments other than those on the current list of parts. There was a long-range navigation aid that came as a box with its own displays and power supplies. Fine for a transport aircraft with a navigator and a plotting table: for a fighter, the information provided by the aid would have to be fed into the avionics system, compared with other sources navigational data, and a 'best estimate' value presented automatically on the pilot's and operator's displays.

At the heart of the navigation suite was an inertial navigation system, based around a so-called stable table: a gyroscopically stabilized platform with three orthogonal accelerometers mounted on it. Integrating the accelerometer outputs once gave velocity in each of the three directions: integrating a second time gave distance traveled in the three directions; provided, that is, the stable table was correctly and precisely initialized, and related to the appropriate map in three dimensions, too. Which took a considerable degree of time, and which was essential for a bomber penetrating covertly, deep into enemy territory. It was, however, something of a liability for a fast-reaction fighter that may have to scramble in seconds in response to an alert.

So, the avionics system was initially a collection of separate parts. To make the parts work together, interface units had to be designed and constructed, which would transfer signals and information between the various parts, and a central processing system would be needed to correlate, calculate, etc. And to build the interface units, it was vital to understand precisely how the various equipments worked, how relevant signals could be 'extracted,' what the characteristics of those signals were, particularly in terms of errors, etc., etc. Today, some might refer to such an avionics system using the tautological mantra: 'a system of systems:' then, it was to be an integrated avionics system.

Fighting the aircraft — the missing CONOPS

All of which was a mile away from the immediate concerns of the new avionics system design manager (SDM), just retired from the air force, where he had spent some twenty years in air defense — which might conceivably have had something to do with his getting the new job. While his team busied themselves working on the various technicalities of subsystem integration, and trying to extract blood from the various stones representing the aircraft company, the radar company and the missile company, he addressed a much bigger problem.

The new multi-role aircraft had been designed as a stable, low-level bombing platform at which it was turning out to be very good. However, the very things that made it good as a bomber were the same ones that militated against its air defense role. For a start, the engines were underpowered for an interceptor. Typically, a fighter has excess engine power-to-weight ratio, such that it can accelerate in a vertical climb when fully fuelled and armed, and reach altitudes in excess of, say, 50 000 feet or more. Low altitude bombers do not need that kind of power, and are not provided with it.

Similarly, fighter interceptors are expected to be agile, so that they can turn inside the turn radius of their quarry, and evade air-to-air missiles. Potential agility is indicated, partly, by wing loading: effectively, the force that the wing can sustain in turning flight. Wing loading for bombers is relatively low — they are not required to be that agile.

For fighter interceptors, both excess power-to-weight ratio and high wing loading are de rigueur. The new air defense variant had neither. There was no way that the new fighter could fight — at least, not in the conventional fighter interceptor, 'get stuck in and join the melee' sense. On the other hand, the aircraft had very good sortie duration, much longer than many conventional fighters; long duration meant long time on station, enhanced air patrol and surveillance capability . . . .

The SDM visited old air force chums in government to raise his concerns informally, and see if there were any options. They were as concerned as he. After much soul searching, they realized that the only way in which the new AD variant could possibly operate would be to keep the enemy at arm's length. To achieve the necessary kill rate without being shot down, the air defense variant would have to serve as a 'missile platform,' standing back and launching missiles at a number of targets simultaneously or in rapid succession; the 'smarts' would have to be in the missiles. The air defense variant would not survive if it attempted to 'mix it' with enemy fighter aircraft, which would almost literally run rings around it. Unless . . . .

There was another aspect to consider: one air defense variant on its own would be highly vulnerable, but how about several variants, say two or three, operating together and watching each others backs? The operations analysts worked out a number of scenarios in which two or more variants worked as a team. It seemed to work, but to be effective it required close cooperation and coordination between fighters. And that would require some system redesign to introduce a data link system to pass enemy target data automatically between the interceptors. This would enable the fighter 'group' to automatically allocate targets between them (vital to prevent missiles being wasted by two variants firing at the same target), to triangulate on radar-jamming aircraft, and even to permit one variant to be the 'eyes' of another that had experienced radar failure, and so enabling the latter to still fire his missiles at the right target.

None of this had been considered in the government's air defense variant requirement. Indeed, it became obvious that there was not, and never had been, any credible concept of operations (CONOPS) for the new 'air defender,' either operating singly or in a fleet. Was the air force being sold a pig in a poke?

Meanwhile the systems design team was developing the design of the avionics system so that the two crew members would be able to 'fight the aircraft:' i.e., in addition to flying it, they would also be able to fight with it. A major and continuing concern was the division of labor between front and rear cockpits.

Many fighter interceptors in service are single-seat — the pilot does everything: takeoff, vector to target, detect, locate, track, engage, defend, return to base, land. With a two-man aircraft, the many and various tasks can be shared between the front and the rear cockpit. Moreover, since navigation is less of an issue in a relatively short-range fighter that generally stays over national territory, the rear seat crewmember need not be a navigator: instead, he or she may be a radar operator, weapons manager, multiple-interception planner, etc., or better still, 'mission manager.' Pilots, of course, just love being relegated to the position of 'front-seat jockey!'

The appropriate air force operations branch of government reviewed the system design periodically as it developed. Experienced fighter pilots and navigators populated the branch on tours lasting two to three years, with posts alternating between a pilot and a navigator. Each had their own ideas of how best to fight the aircraft. And that created unforeseen problems.

When a single-seat air force pilot filled the post, he influenced the design towards the front cockpit, with the pilot doing the bulk of the work. When an air force navigator filled the post, he influenced the design towards the rear cockpit, so that the navigator/radar operator/mission manager had much more control.

In retrospect, these problems also arose because of the lack of a CONOPS. No one, not even experienced air defense aircrew, knew how to fight this new hybrid animal.

The problem was highlighted by the capability of the new radar. It was of a new type, with excellent lookdown capabilities: it could look down from high altitude and see moving targets beneath it without the confusion of echoes from the stationary ground. It also had the ability to track-while-scan, i.e., it could track a number of targets while the radar dish was still scanning back and forth.

Bearing in mind that the new variant could not 'mix it' with other fighters, and that it would have to stand back from any melee, the system designers realized that the new radar would allow the crew to set up a sequence of interceptions, rather than engage just one target at a time. It was possible to:

- track a number of targets;
- plot an intercept line that ran past the targets in sequence, or perhaps even in parallel;
- launch weapons at the appropriate points in the sequence 'run;'
- maintain a watch on other target tracks and plots;
- connect other targets into the sequence, to 'keep it going,' until they ran out of weapons or fuel.

Conceptually, at least, this might start to offset the disadvantages that the new variant inherently possessed: it was to be a way of fighting, but it seemed feasible.

To test out that feasibility, the design team approached an air force unit dedicated to developing, trialing and teaching tactics: it seemed the sensible thing to do. The unit was populated by pilots and navigators with considerable experience at operating aircraft already in air force service, and therefore designed some 20–30 years earlier: they had no knowledge of more recent technology, and no idea how to take advantage of it tactically. In essence, they only knew how to fight their old aircraft using only old technology . . . .

Government reluctance

With a possible way of fighting the aircraft in mind, the system design team set about designing the system to enable the 'hand of purpose,' i.e., to develop the functions and processes that would allow the crew to perform their tasks, examine their sensors, manage their weapons, engage their targets, defend themselves against attackers, fight their aircraft and cooperate with others.

One of the most important capabilities needed, in view of the variant's proposed 'standoff' fighting philosophy, would enable the crew to engage a number of targets simultaneously. The variant would have two kinds of air-to-air missiles: a shorter range, infrared seeker, fire-and-forget missile, nominally for self-defense; and a longer range semi-active homing missile that required its target to be illuminated by the interceptor's radar before and during missile flight. The shorter-range missile was no problem — it could be locked to a target's IR signature, launched and left to 'do its thing.'

The semi-active homer was problematic. The missile system was designed with an earlier kind of radar in mind. Earlier radars had a single dish, which stopped scanning when the radar locked on to a target, and the dish pointed thereafter at the target. Coupled to the dish would be a 'CW illuminator,' a continuous wave radar transmitter that shone a beam of energy at the target. It was the reflection from this beam that the semi-active homer missile detected, locked on to and followed. The target had to be illuminated for the whole flight time, else the missile would 'lose sight of' the target and miss.

The variant's new radar, however, was a track-while-scan (TWS) radar, with all the advantages that afforded for multiple target tracking and multiple target engagement. Its CW illuminator was physically locked to the scanner dish, so that the CW illuminator wagged back and forth with the main dish. If the whole dish assembly, including the CW illuminator, had to be locked to the target sightline to engage the missile with its target, and for the duration of missile flight, then the radar would, for that time at least, no longer be a TWS radar — it would not be scanning at all.

The solution seemed straightforward, conceptually at least. If the new variant was to be able to engage several targets at range simultaneously or in rapid succession, then the TWS had to be in operation, and the targets and missiles had to be illuminated too, but only part time as the scanner swept the CW beam across them. Otherwise, it would be necessary to have separate scanners, one for steerable multi-beam CW illumination and the other for the TWS radar. The first solution required modifications to government's specially developed missile: the second solution required modifications to government's specially developed, advanced radar.

Government would countenance neither solution; no modifications would be allowed to their fixed-price, fixed-specification development contracts. Which shot rather a big whole in the only feasible fighting philosophy that the system design team had developed. So, still no credible CONOPS . . . this would be like a man on crutches, wearing boxing gloves, taking on a group of ninjas wielding samurai swords!

Systems concepts — triangulating ghosts

Back to the drawing board. The threat was alleged to include jamming aircraft, which may prevent the TWS radar from tracking targets: instead, the radar screen would show a line on the azimuth angle corresponding to the direction of the jammer.

Two cooperating variants could exchange the azimuth angle at which they respectively perceived the jamming target. Plotting own position and cooperating variant's position with the respective azimuth angles resulted in a cross on the map display: this was triangulation on the jammer and it could be accomplished automatically, provided the two variants had a data link to enable data exchange between them.

Suppose, instead, there were two jammers, or three . . . for N jammers there would be N^2 triangulation points, or crossovers, only N of which would be real; the remaining $N \times (N - 1)$ would be 'ghosts.' The systems design team got to work and came up with several ingenious schemes for picking out the real target from the ghost target. They all depended on automatic exchange of data between cooperating aircraft using some form of data link. There was no data link in the original requirement, however: without a CONOPS, who would have perceived the need?

Systems concepts – LANCE

The SDM came up with an idea (allegedly while taking a bath with his big toe up the spout of the cold tap). Since the TWS radar could track a number of targets simultaneously, it could provide the data to draw target vectors on the radar map, with each vector showing the respective aircraft's track, and the vector's length corresponding to its speed. Similarly, it was possible to draw a vector in front of the symbol for own aircraft, but this time showing the maximum relative range (MRR) of the missile. MRR is a useful measure: when a missile is fired, its motor provides an impulse, which takes it rapidly to high speed; thereafter, with the motor burnt out, the missile coasts to its target, slowing down as it does. As it slows down, the launch aircraft starts to overtake it. So, there will exist a point at which the missile reaches its furthest distance from the launch aircraft — this is the MRR. Beyond the MRR, the launch aircraft starts to overtake the missile, which may still be a long way ahead. The MRR represents the farthest distance/earliest point at which an intercept can be made.

Suppose now that a vector is drawn on the electronic map protruding from the interceptor variant's symbol, showing the MRR for the missile, and the number of seconds from launch to reach that maximum relative range, T_{MRR}. Draw a small circle at the end of the vector to mark the spot. Suppose, too, that the vectors in front of each target track are scaled to show where each target will be in T_{MRR} seconds: put a small cross at the end of each vector to mark the spot.

If a pilot flies his aircraft so that the missile vector's circle lays over a target aircraft's cross, then the coincidence represents the point where both missile and target will be in T_{MRR} seconds; i.e., the earliest engagement point.

One of the team named this idea LANCE — line algorithm for navigation in combat environments. The analogy of a lance protruding in front of the aircraft was apt. All the crew had to do was to fly the aircraft so that the tip of the LANCE lay over the tip of a target track vector, and press the button! The concept was ideal for the air defense variant, since it would enable the variant to keep its distance, and to stand back as far as possible from any melee.

LANCE was a natural — government liked it, air force fighter crews like it, it seemed to have everything going of it. Except. The aircraft manufacturer, still no-doubt smarting because he had not won the avionics system design contract, incorporated a prototype version of LANCE on the development rigs in the factory, and decided that the display was 'too unstable,' and therefore impractical. Perhaps it was . . . .

Six months later, virtually the same idea was incorporated in another nation's fighter aircraft under a different name. Not too unstable for them, then? Now, there's a thing.

Conclusions

It is interesting to note, from this cautionary tale, just what systems engineering was, and always is, about. It was operating at two levels:

- First and foremost, it was trying to understand the problem facing the crew in achieving their purpose, and to provide them with the facilities and services they would need, not just as isolated crews, but as members of a group or fleet of defending aircraft.
    - This was not engineering — this was 'system operations design,' for want of a better term — working out how the whole system, with the crews at its foci, is going to achieve its mission, fulfil its purpose.
- Second it was configuring and integrating the various technological facilities, including sensors, weapons, displays and controls, so that the various mission functions could be choreographed, activated, orchestrated and controlled by the crew, working in cooperation with other crews as necessary.

- This was not engineering, either — this was systems design, tracing and forging the 'hand of purpose' from crew member, through controls, subsystems, interfaces, subsystems and — generally — back to the crew. Or, if you prefer, enabling the crew to orchestrate and conduct operations and prime mission functions

The system design team, many of them excellent engineers, physics graduates, systems analysts, operations analysts, etc., were obliged to try and establish a CONOPS. They did as well as they could, but should this have been their job? I refer to the bastardized quotation at the beginning of the chapter.

And the aircraft: how did it fare in service? Well, let us put it this way. It was not the best fighter the air force ever had. It went through a number of marks and improvement phases during which some of the original shortcomings were recognized and rectified — but not all. As usual in such cases, the motivation, training and excellence of the aircrews managed to overcome many of the shortcomings, even if they were effectively fighting with one hand tied behind their backs.

And, come to think of it . . . the whole project was systems engineering with one hand tied behind its back, too.