Autonomous Flight Control and Software Literature Review

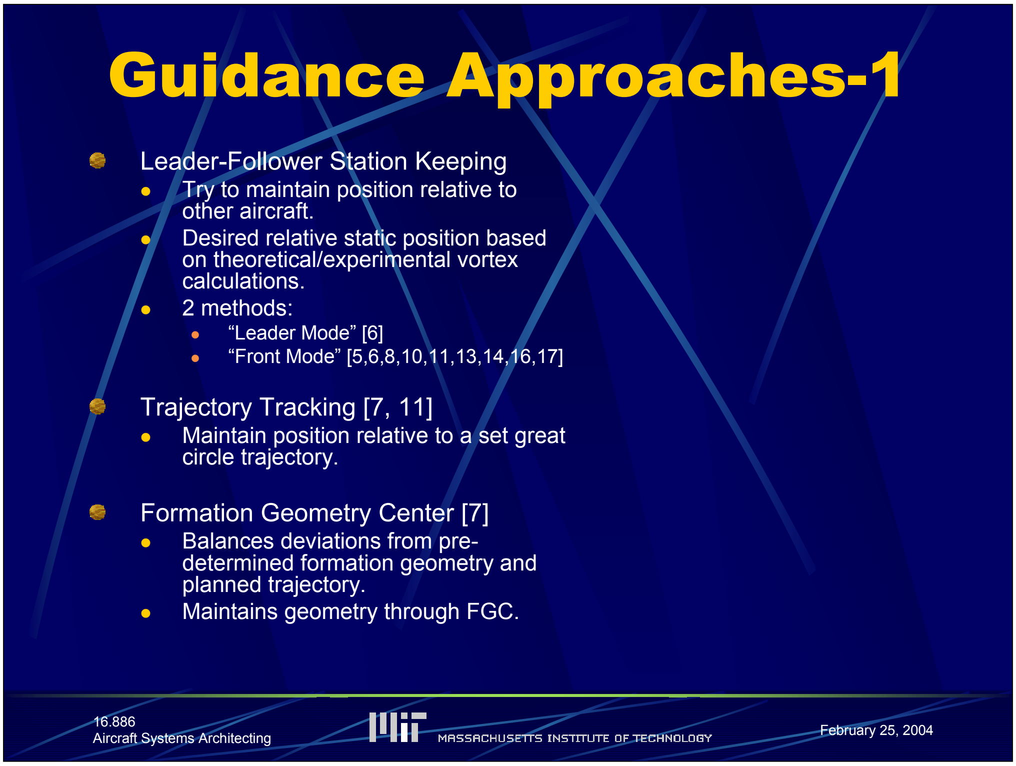
16.886 - Aircraft Systems Architecting

Paul Mitchell

February 25, 2004

Overview

- Guidance Approaches
- String Stability
- Autopilot & Software Capabilities
- References



1. Leader-Follower Station Keeping

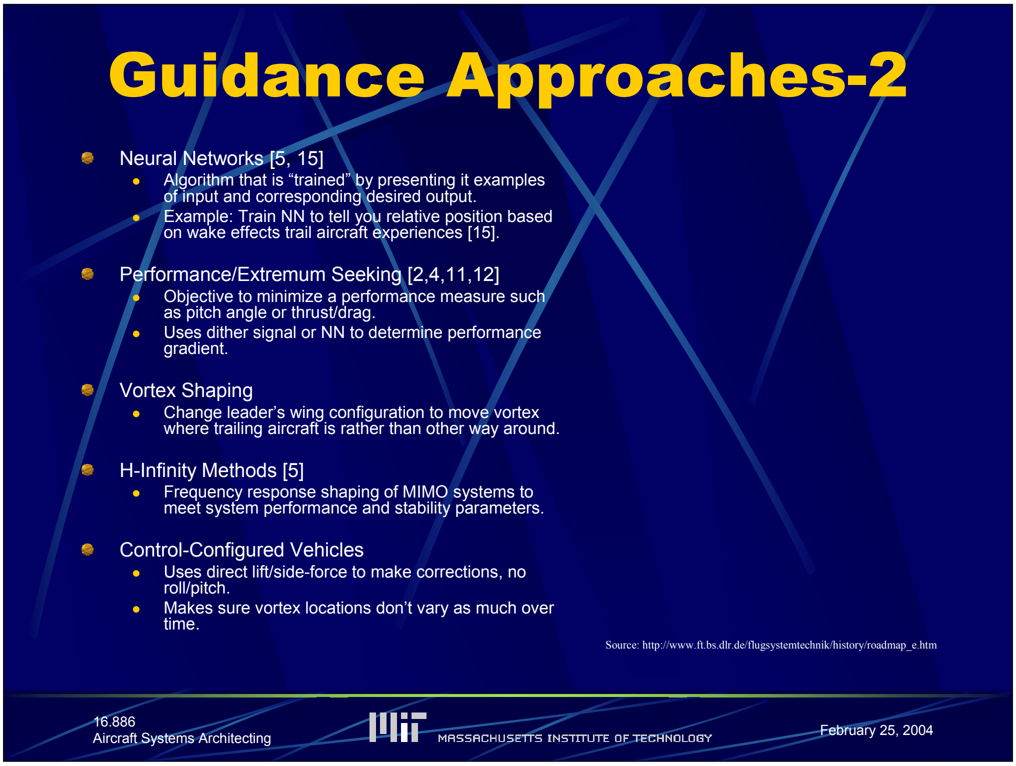
This is the standard guidance method that was first presented by Greg Larson earlier this month. There has been a lot of literature written on this method, starting with Hummel and constantly improved upon by others such as Lavretsky, Guilietti with adaptive control methods. Through NASA’s AFF program, this is the only guidance method from my list proven to work in actual manned formation flight. In this method the control algorithm tries to maintain a static position relative to another aircraft in the formation. This static position is pre-determined, either by aerodynamic theory (relatively undeveloped) or experimental data (expensive). There are two types of station keeping, “leader mode”, where each aircraft maintains a relative position to a designated leader aircraft, and the more commonly investigated “front” mode where relative position is held in the vortex of the wingman (men?) directly ahead of the trailing aircraft. The wingman directly ahead of a trailing aircraft may coincide with the formation leader, but this isn’t necessarily so as formation numbers rise above 3. As we are primarily concerned with staying in the vortex of the aircraft directly ahead, “front” mode seems to make a lot of sense. However, [6] makes a valid point in that string stability may become an issue with the “front” mode that is less of a problem than in “leader” mode. More on that later.

2. Trajectory Tracking

This is another method presented by Greg Larson. It’s pretty simple and is appropriate if you have a set trajectory with no arbitrary maneuvers. Trajectories are defined ahead of time relative to one another, and the algorithm tries to maintain those set paths. This isn’t investigated in the literature too much for some reason, but I can see benefits to using it. It certainly is easy to do from a control standpoint and doesn’t require accurate relative position measurements. However, it is also the most inflexible method.

3. Formation Geometry Center

This concept is based off of observation of the natural flight behavior of birds that maintain a defined geometrical shape, but if one or more of the birds loses its position in the formation, the flock waits (or holds back) for those birds to rejoin the formation. The original trajectory is modified to accomplish this. So this algorithm tries to maintain formation geometry (thus, relative positions can be maintained) while at the same time tracking a prescribed path for each aircraft. If an aircraft loses its position, the formation senses it, acts together to restore geometry, then moves back to tracking the correct path. This combines pure trajectory tracking with a variant of the station-keeping concept. The formation geometry center (FGC) is an imaginary point that depends on the integral of the average of formation speeds, headings and flight path angles. The geometry center concept could be implemented independently. Only simulations were done and only with 2 aircraft in standard V-formation, with good results.



1. Neural Networks

Neural Networks are software programs that have the ability to be trained by presenting the program examples of input and the corresponding desired output. NN are receiving a lot of attention in many different areas, primarily NOT in formation flight, but it has been tried in very limited simulation. [15] presents a framework for getting a NN to tell you relative position based upon the wake effects the trail aircraft is feeling and shows that it is possible in practice. Care must be taken to have an excellent training set for good results. Also mentioned in [5] by Boeing as an area for possible development in the NASA AFF project.

2. Performance/Extremum Seeking

The objective of this algorithm is to minimize a performance parameter, in formation flight typically the trailing aircraft’s trim pitch angle or thrust. It does not need to know any information about a vortex model. This area is still quite under-developed and most theory [2,4] places the aircraft near the desired position, then moves opposite the gradient of the measured performance function. This requires the introduction of a dither (periodic) signal for the system to sense the gradient, which is highly undesirable. Other methods using neural networks to “sense” the gradient have also been tried [12]. Simulations have been done with 2 F/A-18s [12] and C5s [2] in formation, but no flight tests as yet.

3. Vortex Shaping

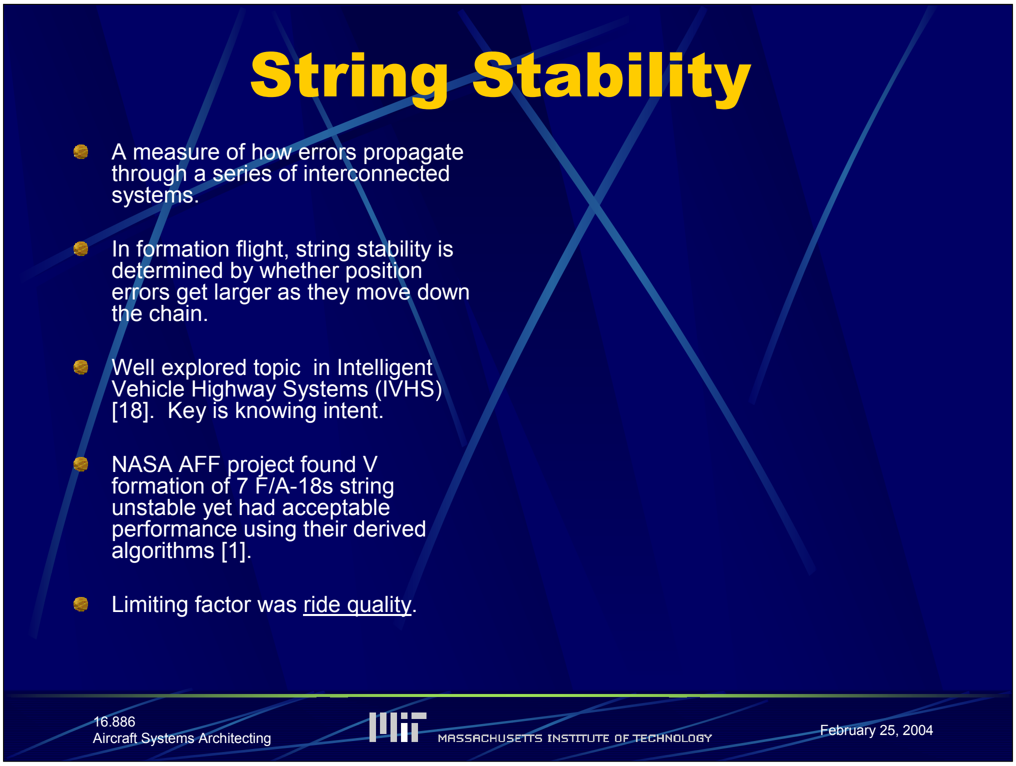
This is an idea that has come up in discussion with MIT & Stanford professors such as Murman, Deyst, etc. but I have not been able to find any literature thus far on this method being investigated. What this would involve would be some sort of manipulation of the wingtips/wings of the aircraft creating the vortices so that the vortices themselves move instead of the trailing aircraft, ie. we bring the vortex to the aircraft instead of the other way around. It’s definately a different way to look at things. Major limitations I can see: Would require non-trivial (structural) changes to the expensive wings on existing aircraft, plus we really don’t have a good enough model of the wake of an aircraft to be able to predict with enough accuracy where aircraft changes will move the vortices.

4. H-Infinity Methods

This is a relatively new control method that takes performance and stability goals for the system and translates them into limits on the infinity norm of the transfer function for the MIMO system. The frequency response of the system is manipulated to achieve desired results. I don’t know how exactly this applies to formation flight, but I included it as it was mentioned as a possible future direction in [5] for the NASA AFF project.

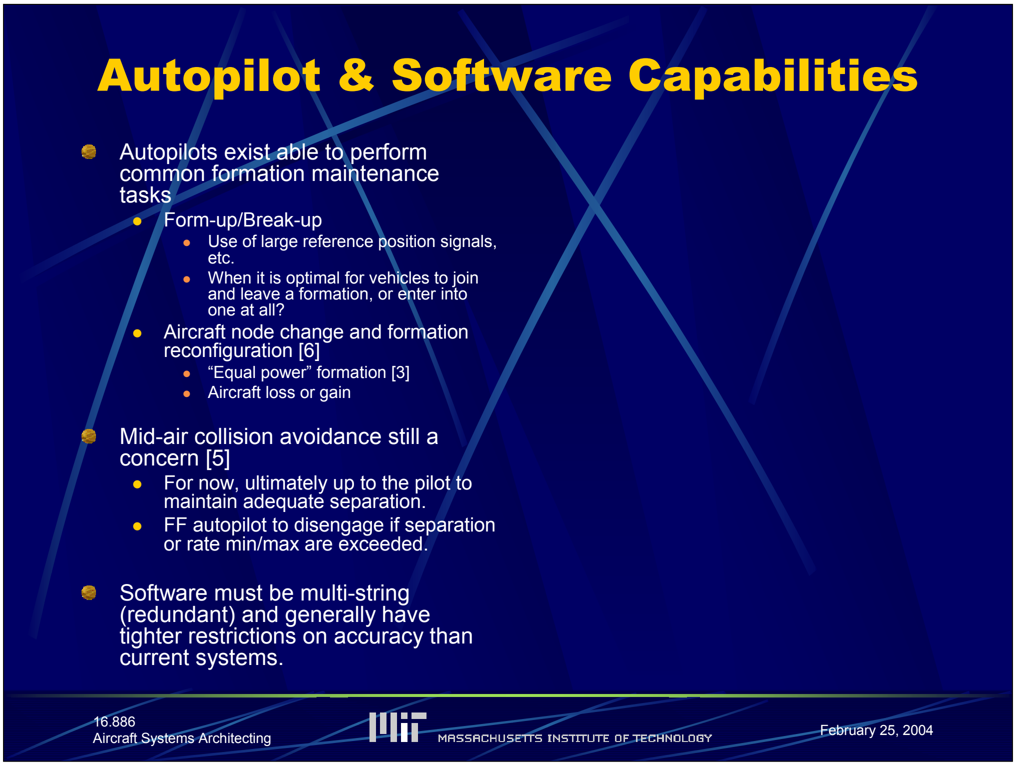
5. Control-Configured Vehicles

This is not so much it’s own separate method of guidance for formation flight as a way to possibly complete in-flight adjustments more efficiently. This would involve utilizing direct lift and side force actuators to accomplish lateral and vertical motions to correct small errors in position. Doing so would mean that trailing vortices would not move up or down due to pitch or roll. We don’t yet know the effects of pitching/rolling to correct and how much it is possibly costing in fuel economy as opposed to this method. Using this method, auxiliary engines could be used that are designed for finer adjustments that would use less fuel overall. Control-configured vehicles have been utilized in other applications such as UAVs, but not for formation flight to my knowledge. The picture to the right is Dassault/Dornier Alpha Jet Direct Side Force Control (DSFC) demonstrator aircraft of the German Air Force.



String Stability

String stability is a measure of how errors propagate through a series of interconnected systems. In the case of formation flight, string stability is determined by whether position errors in the front of the formation get larger or smaller as they move down the chain. This is a topic that has been well explored in the IVHS program. The results out of that program are that string stability can be achieved with constant separation distance if each vehicle knows the relative velocity or position of the lead vehicle AND the one in front (may be the same). If separation distance can vary with speed, then only the absolute velocity of the vehicle and the relative velocity of the vehicle in front are required. [18] hypothesizes that these same requirements will result in string stability of formation flight as well, though there are complicating factors. [1] experiments with a string unstable system and gets results that say that string instability may be OK, especially for smaller formations. For example, in the graphs to the side demonstrate a simulation of F/A-18 aircraft in light turbulence with the last aircraft still mostly staying within the project goal of within 9ft relative position accuracy. Limitation comes in when you consider the accelerations that the pilots experience. A measure of this is the “ride quality” given by the motion sickness dose values (MSDV) issued by the ISO. MSDV is a frequency-weighted acceleration in the z-direction. It can be seen that with all the more aggressive gain sets we get above the limit set on the graph, which is where 10 percent of the general population would vomit after an hour of flight in those conditions.



Autopilots can do just about everything we want in formation flying. For form up, a pilot could activate a formation flying autopilot which would track to a specific point relative to another aircraft, provided to begin with the two planes were close enough. To leave a formation, pilots could specify a new relative position outside the formation before taking the controls. Rough algorithms in simulation also have been able to perform more dynamical tasks such as switching leaders in a formation (as described in Multhopp for "equal power" formation) and changing formation geometry when the number of aircraft in the formation changes due to one leaving or joining up. On the right you can see a simulation of this sort of thing happening where the leader of the formation drops out the back and the formation adjusts to compensate for this, with another aircraft becoming the new leader.

Software is not up to flight critical standards for formation flight just yet. As such (and even when it is), mid-air collision is always a concern. Warnings can be provided to the pilot and the formation flight autopilot can disengage automatically when minimum separation distances or maximum separation rates passed. The normal airplane autopilot can still be engaged at this point if desired. Indeed, this was exactly the case for the NASA AFF project. In order to prevent system failures, redundancy needs to be build into the software.

References

[1] Allen, M.J., Ryan, J., Hanson, C.E., and Parle, J.F., “String Stability of a Linear Formation Flight Control System,” AIAA Paper 2002-4756, Aug. 2002.

[2] Binetti, P., Ariyur, K.B., Krstic, M., and Bernelli, F., “Formation Flight Optimization Using Extremum Seeking Feedback,” *AIAA Journal of Guidance, Control and Dynamics*, Vol. 26, No. 1, 2003, pp.132-142.

[3] Blake, W.B., and Multhopp, D., “Design, Performance and Modeling Considerations for Close Formation Flight,” AIAA Paper 98-4343, Aug. 1998.

[4] Chichka, D.F., Speyer, J.L., and Park, C.G., “Peek Seeking Control with Application to Formation Flight,” *Proceedings of the 38th IEEE Conference on Decision and Control*, pp. 2463-2470, Phoenix, AZ, Dec. 1999.

[5] Cobleigh, B., “Capabilities and Future Applications of the NASA Autonomous Formation Flight (AFF) Aircraft,” AIAA Paper 2002-3443, May 2002.

[6] Guilietti, F., Pollini, L., and Innocenti, M., “Autonomous Formation Flight,” *IEEE Controls System Magazine*, Vol. 20, No. 6, 2000, pp. 34-44.

[7] Guilietti, F., Pollini, L., and Innocenti, M., “Formation Flight Control: A Behavioral Approach,” AIAA Paper 2001-4239, Aug. 2001.

[8] Hanson, C.E., Ryan, J., Allen, M.J., and Jacobson, S.R., “An Overview of Flight Test Results for a Formation Flight Autopilot,” AIAA Paper 2002-4755, Aug. 2002.

[9] Houck, S., and Powell, J.D., “Visual, Cruise Formation Flying Dynamics,” AIAA Paper 2000-4316, Aug. 2000.

[10] Hummel, D., “The Use of Aircraft Wakes to Achieve Power Reduction in Formation Flight,” *Proceedings of the Fluid Dynamics Panel Symposium*, AGARD, 1996, pp. 1777-1794.

[11] Larson, G., “Autonomous Formation Flight,” Presentation to MIT 16.886 Class, 05 Feb. 2004.

[12] Lavretsky, E., Hovakimyan, N., Calise, A., and Stepanyan, V., “Adaptive Vortex Seeking Formation Flight Neurocontrol,” AIAA Paper 2003-5726, Aug. 2003.

[13] Lavretsky, E., “F/A-18 Autonomous Formation Flight Control System Design,” AIAA Paper 2002-4757, Aug. 2002.

[14] Misovec, K. “Applied Adaptive Techniques for F/A-18 Formation Flight,” AIAA Paper 2002-4550, Aug. 2002.

[15] Pollini, L., Guilietti, F., and Innocenti, M., “Sensorless Formation Flight,” AIAA Paper 2001-4356, Aug. 2001.

[16] Proud, A.W., Pachter, M., and D’Azzo, J.J., “Close Formation Flight Control,” *Proceedings of the AIAA Guidance, Navigation and Control Conference*, pp. 1231-1246, Portland, OR, Aug. 1999.

[17] Schumacher, C.J., and Singh, S.N., “Nonlinear Control of Multiple UAVs in Close-Coupled Formation Flight,” AIAA Paper 2000-4373, Aug. 2000.

[18] Wolfe, J.D., Chichka, D.F., and Speyer, J.L., “Decentralized Controllers for Unmanned Aerial Vehicle Formation Flight,” AIAA Paper 96-3833, Jul. 1996.

References for further depth on the material that was just presented.