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Using Airborne Vehicle-Based Antenna Arrays to Improve Communications with UAV Clusters

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***Abstract* - Recently, there have been many proposed applications for clusters of small Unmanned Aerial Vehicles (UAVs). Some of these applications, such as Synthetic Aperture Radar and video surveillance, can generate large quantities of data which must be transmitted to a base station quickly. UAV size limitations often prevent the use of large, highly directive antennas in this link with the base station. This paper proposes the solution of forming an antenna array from several UAVs and applies antenna array theory to analyze its performance. An example is given where phase compensation is used to achieve high directivity even in the presence of element position errors.**

I. COMMUNICATION WITH UAV CLUSTERS

As UAV capabilities improve, more and more applications are emerging where groups or clusters of UAVs can perform tasks more efficiently than single UAVs or other vehicles. A clear example of this would be Synthetic Aperture Radar where an area is illuminated with radio frequency energy and the scattered field is sampled at a number of points by a small antenna. The resulting data is then post-processed to yield an image with a resolution which would have required a much larger antenna if the image were taken from a single point. Traditionally, this is accomplished by flying an aircraft or satellite in a raster scan pattern. A cluster of UAVs, however, could conceivably accomplish the same task in much less time by sampling multiple spatially-separated points simultaneously, similar to what has been proposed for formations of satellites using tight formation flying techniques [1,2].

A second example is video surveillance. A number of UAVs could be deployed in an area such as a small town and each vehicle be assigned a section of the town to monitor. Each UAV could take video clips or still photographs of its own surroundings. Both applications mentioned here, as well as many others, have the potential to generate large quantities of data that must be transmitted to a distant base station or satellite under time constraints.

According to the Shannon-Hartley Theorem, when maximum channel capacity modulation formats are used in a radio-frequency communications link, the capacity in bits per second varies linearly with the signal to noise power density ratio [3]. Operational restrictions such as the ability to enter confined spaces or to avoid detection may require that small UAVs be used, which would limit both the maximum transmitted power and antenna size, in turn severely limiting the attainable data rate.

A possible solution to this problem would be to form an antenna array whose elements are the antennas on each of the UAVs in the cluster. In this situation, the UAVs would first share the information to be transmitted among each other and then perform data aggregation, compression, and additional processing such as feature extraction to condense the data as much as possible. Future research could elucidate the best methods of doing this for each particular application.

Following the additional processing, the UAVs would fly into a formation conducive to good array performance and then transmit together, using electromagnetic interference to focus their limited power in the direction of the intended receiver. Not only does this have the advantage of combining their transmitted power, but it also improves the situation further by sending more of this power in the direction of the receiver, causing less waste. This property of antennas, called directivity, is the primary reason, beyond inefficiencies of very small antennas, why an antenna with large spatial extent has an advantage over a smaller one.

The idea of forming an antenna array from several vehicles has been explored to some extent [4], but a thorough examination of the problem for UAVs, including an analysis of the expected performance in the unique airborne environment, is lacking. This paper attempts to provide some of this analysis by means of a realistic worked example with simulation results.

The primary challenge to producing a usable airborne vehicle-based array antenna is position errors. Wind and other disturbances prevent the vehicles from remaining in the ideal designed array locations. This causes a reduction in antenna directivity which can be largely compensated electronically if the vehicle positions are known. Therefore, a combination of **good vehicle control** and **good position sensing** are the central requirements for a practical vehicle-based antenna array solution to the UAV communications problem.

II. EVALUATING LINK QUALITY

The goal of an antenna system in a long distance point to point communications link is to transfer as much power as is feasible from transmitter to receiver. For purposes of comparing antenna performance, it is useful to introduce the concept of an isotropic radiator. This conceptual antenna transmits power equally in all directions, so that at any given radius from the transmitter site, the area power density is simply the transmitted power divided by the area of a sphere of that radius. Furthermore, since receiving antennas can be characterized by an effective area, the ratio of power received to power transmitted for an isotropic transmitter is given by:

$$Q = A_{EFF}\frac{1}{4\pi r^2} \qquad (1)$$

referred to here as Q or the link quality factor. Although the concepts in the paper could also be applied to UAVs which need to receive data, for conceptual clarity this analysis is focused on the problem where the receiver site has an antenna of fixed and known effective area and the UAV cluster must transmit data to the receiving site.

Real antennas are not isotropic, but instead transmit more power in some directions than in others. Numerically, directivity is the ratio of the power transmitted in a given direction to the power that would be transmitted in that direction by an isotropic antenna. When directive antennas are used, the link quality factor Q is improved by a factor of the directivity.

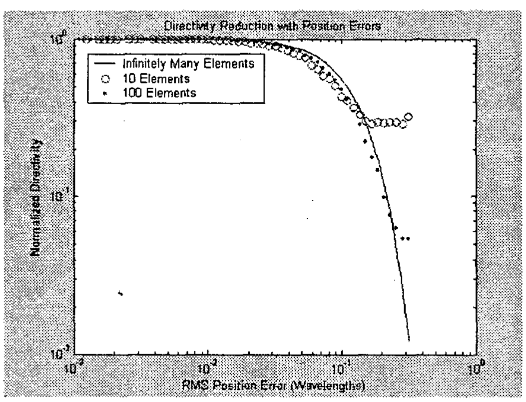


Fig. 1 Effect of position error on maximum (main lobe) directivity

III. THE EFFECT OF ELEMENT POSITION ERRORS

The primary difference between a traditional antenna array and a vehicle-based array is that the former is usually constructed on a rigid structure which ensures constant, nearly perfect element positioning, while a vehicle-based array must contend with wind gusts and turbulence. The resulting element position errors, or deviations from ideal positions, have two effects: reduction of directivity in the desired direction and an increase in directivity in other directions. In other words, it tends to make the array more isotropic.

The effects of element position errors have been investigated primarily by those interested in maximizing the performance of large array antennas [5]. It was found that, in the limit of an array with an infinite number of elements, the statistical average of the maximum directivity has an exponential dependence on the variance of the position errors. Analytically:

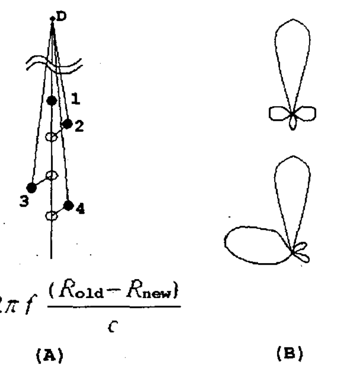
$$D = D_o\left(\frac{1}{1+\frac{1}{2}\pi\left(e^{(2\pi\sigma)^2}-1\right)}\right) \qquad (2)$$

where D is the directivity with errors, D_o is the directivity without errors, and σ is the root mean square position error in wavelengths. Fig. 1 shows this along with simulation results of two finite arrays with position errors. The vertical axis is directivity normalized to the ideal, error-free directivity of the array. The horizontal axis is the root-mean-square position error for each of the three spatial dimensions (assuming that the RMS error is the same in all three dimensions).

The two finite array cases used were both linear arrays, one of 10 elements and the other of 100 elements. The elements are ideal half-wave dipoles fed with current sources of identical amplitude, but with the phases adjusted according to the Hansen-Woodyard criterion for an endfire array [6]. The individual elements have a directivity of about 1.67 and the error-free directivity of the two linear arrays are 23.2 and 185.7 respectively.

Because of conservation of energy, it is not possible for the maximum directivity of an array to be less than one, so it is clear that the function for a finite case cannot be identical to that of the infinite case, which continues to lower and lower values of normalized directivity. Fig. 1 shows that the results for the finite case match those of the infinite case closely until a directivity of slightly more than the directivity of an individual element is reached.

For radar applications and other situations where interference rejection is a factor, the directivity in undesired directions is important. Expressed as a ratio with the error-free antenna pattern, this is affected more strongly at small levels of position error since the ideal antenna pattern may contain deep nulls. Because this investigation focuses solely on maximizing the distance over which UAV clusters can communicate with a base station, this consideration is left for future study.



$$\Delta\phi = 2\pi f \frac{(R_{old} - R_{new})}{c}$$

Fig. 2 Traditional phase correction (A) and the effect of antenna pattern on total radiated power (B)

IV. PHASE COMPENSATION

In basic phased array antenna theory, the direction of maximum radiation from the array is the direction in which the signals from each element most nearly add in phase [7]. This naturally leads to the idea that one might be able to compensate for deviations in the positions of the array elements by changing the driving phase of the elements so that their signals add in phase at the receiver. This technique involves two steps: determining the amount by which the phase of the signals from each of the antenna elements, as received at the intended receiving site, has been shifted by position errors, and then applying a corrective reverse phase shift to each respective element of the array. Fig. 2a illustrates this computation, which is based simply on geometric propagation path length changes and the speed of light. That is, the change in the path length, due to position error, from each element to the receiver is computed. Then, the phase of the signal driving each element is shifted by exactly the amount needed to counteract the phase shift due to these path length changes, causing the signals to all add in phase at the receiver.

This "traditional" phase correction works well for small position errors and provided that the element positions are known, it is very easy to compute the necessary corrective phase shifts. However, there are cases where one can do better than simply ensuring that the element signals still sum in-phase at the receiver. This is due to the fact that the actual power radiated by the antenna is the integral of that radiated in all directions. See fig. 2b. If one compares two antenna patterns, both with the same main lobe but one of which has a large secondary lobe, then the one without the secondary lobe will have a greater directivity, even though it radiates the same amount of power in the intended direction. What is being held constant between the two antennas is the magnitude of the currents in the elements. The difference in directivity is because the one with the additional lobe requires more input power to achieve the same radiated power in the desired direction.

Traditional phase correction assumes that altering the phases will not change the relationship between element current and radiated power (the radiation resistance) significantly. Often this is true but not always. Table 1 compares traditional phase correction to the optimal case for a simple two-element array with a spacing of 1/8th wavelength. The optimal phase for the second element was computed by doing a local maximum search with the MATLAB command FMINSEARCH, which uses the Nelder-Mead simplex method [8].

The best method of phase compensation is dependent on the exact application, with the most important factor being how close the elements will be spaced. If the elements do not interact by receiving power from adjacent elements then the total transmitted power will not depend on the element positions and the "traditional" method will be the optimal. Determining the best phase compensation method in each circumstance could be the subject of future research.

TABLE I
COMPARISON OF TRADITIONAL PHASE COMPENSATION WITH DIRECT SEARCH METHOD

Type of Phase Compensation	Phase	Directivity
Traditional	-45.0 degrees	3.14 dBi (2.06)
Local Search	-162.3 degrees	7.45 dBi (5.56)

V. AN EXAMPLE: AN ARRAY OF 10 CORNELL AUTONOMOUS FLYING VEHICLES (AFVs)

To put all of this in proper perspective, it would be useful to see a worked example in a practical case. As part of a research effort into formation flight of unmanned aerial vehicles, our research group at Cornell is working on a four-rotor helicopter-type vehicle called the Autonomous Flying Vehicle (AFV). A photograph of the AFV is shown in fig. 3 and some specifications are given in table 2.

The Cornell AFV is designed as a dynamics and control testbed to investigate aerobatic maneuvers and aggressive station-keeping for small rotorcraft. Such four-rotor designs, like the Draganflyer, have recently become popular in hobby model aviation [9]. Some research efforts have also investigated using this mechanically-simple configuration for centimeter-sized UAVs, like the Mesicopter [10]. Because our focus is on dynamics and control and not flight hardware technology, we are not constrained by size. The tools developed for the Cornell AFV should easily scale to much smaller vehicles, as long as low Reynolds number effects are taken into account for the extreme of the small size scale.

We now analyze how one could construct a communications link between a cluster of 10 Cornell AFVs and a base station 100 kilometers distant, such as a satellite.

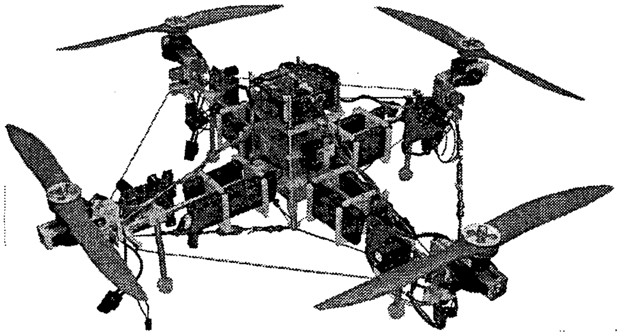


Figure 3 Photo of Cornell Autonomous Flying Vehicle

For the purposes of this simulation, wind disturbances are modeled by simply assuming that wind affects the vehicle only via the rotors and flat-plate drag on the central mass and that wind speed is a Gaussian bandlimited white noise source with an RMS magnitude of 10 miles per hour, with a bandwidth of 10Hz. Since this model assumes that the wind gusts experienced by each vehicle are uncorrelated, this is a worst-case model for wind behavior.

TABLE II
CORNELL AFV SPECIFICATIONS

Parameter	Specification
Dimensions	1.5 x 1.5 x 0.4 meters
Mass	6 kg
Linear acceleration	1 g maximum
Angular acceleration	2 rad/second^2
Rate gyro noise	0.035 deg/root hour
Rate gyro drift	3 deg/hr
Position uncertainty	0.1 meters
Motor time constant	40 milliseconds

Consider that the base station antenna is a simple half-wave dipole (perhaps because it cannot be steered and must be able to receive from all directions) operating at 150 MHz. This would have an effective area of 0.52 m^2. Assume that the same kind of antenna is used on each AFV and that the receiver must receive -70dBm to ensure a reliable communication link. This means that 14 Watts is required if each AFV transmits by itself.

Before we can determine the performance of the array, we need to know the magnitude of the position errors. A simple H_∞ control design was done for the AFVs. This controller does not take into account the presence of the other AFVs and is therefore a totally decentralized controller, providing a worst-case formation performance bound. In future research, existing methods for distributed control design could be used to develop a more effective controller [11,12]. The MATLAB script to perform this basic control design, along with a simple linear model of the AFV, is available at the first author's web site.

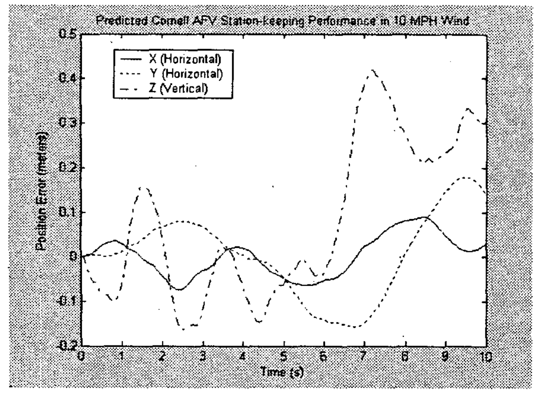


Fig. 4 Predicted Cornell AFV performance in wind.

Fig. 4 shows the results of closed-loop simulation of a single AFV with wind disturbances. Since a wavelength is approximately 2 meters at the operating frequency, this represents worst-case position errors of about 0.05, 0.09, and 0.2 wavelengths in the X, Y, and Z dimensions, respectively. The Z dimension disturbance is greater because of the larger effect that wind in the vertical direction has on the rotors.

A linear endfire array of 10 dipole elements was designed and provides 12.1 dB gain over a single dipole. Fig. 5 shows how the directivity of the array would change if it were vehicle-based using the formation of 10 Cornell AFVs. This is shown without phase compensation and with local direct search-based phase compensation.

Using the worst case from the phase compensated array, the antenna shows a directivity of 15.3, which is 9.6 dB gain over a single dipole, allowing the AFV cluster to communicate reliably with the base station 100 km away with only 1.5 Watts.

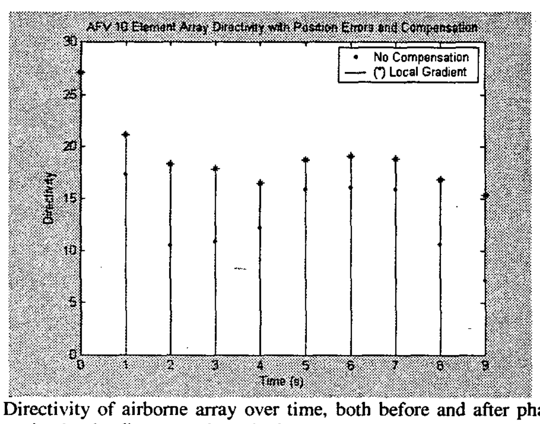


Fig. 5 Directivity of airborne array over time, both before and after phase compensation by the direct search method.

VI. CONCLUSION

While, to our knowledge, an actual physical demonstration of the feasibility of an airborne vehicle-based antenna array has yet to be done, the simulation-based example given here shows that it is realistic to think that a significant improvement in link quality can be achieved by forming an antenna array using elements on several airborne vehicles. This could significantly enhance the communication abilities of small unmanned aerial vehicles, or alternatively, decrease the power required to achieve a reliable communications link over a long distance.

In future efforts it would be worthwhile to investigate the special cases of a vehicle-based array where maximum antenna pattern sidelobe amplitude is a concern, perhaps using a version of existing adaptive array techniques, or the situation where the maximum transmitted power is limited on a vehicle by vehicle basis rather than simply a limitation on the array as a whole [13]. There are also many other interesting research challenges associated with this problem, such as developing efficient distributed algorithms for data aggregation, phase compensation, and vehicle control.

VII. ACKNOWLEDGMENTS

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