Performance of an Embedded Monopole Antenna Array in a UAV Wing Structure

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Abstract—In this work we present a small size, printed monopole antenna embedded within the wing structure of a small Unmanned Aerial Vehicle (UAV) and operating in the 2.4 GHz ISM band. Integration of antenna elements within UAV structures will reduce the weight and cost. Also, the use of embedded antenna arrays will increase the communication range and data throughput. 4-element and 8-element embedded uniform linear antenna arrays are modeled, simulated and studied. Simulation and measurement results for the resonant frequency of the basic element were performed. Results showing the HPBW and SLL of the simulation models for different excitations for the wing structure antenna array are presented and compared.

I. INTRODUCTION

Unmanned aerial vehicles (UAV) are widely used in military and exploration missions. They are used routinely to collect and send information back to a ground station that provides real-time information on the covered area. Flying UAVs have several advantages over their land counterparts, primarily their ability to cover a wider area. The data transmission from both kinds of UAVs is done via wireless links. Single antennas and antenna arrays are being used for sending the data back to the ground station for analysis and decision making. NASA is supporting major UAV projects for terrestrial as well as space missions [1], [2].

Antenna arrays are widely used in communication systems. They provide higher signal to noise ratios (SNR) on the received signals, higher directivity, higher antenna gain, and the capability of steering the antenna radiation pattern to track the transmit/receive antenna. Examples of use of antenna arrays are evident in wireless cellular base stations and wireless 802.11n. Antenna arrays can be designed to perform beam steering and null steering. The former will allow the antenna array to direct its radiation beam into a pre-specified direction according to an optimization criteria, i.e., the incoming carrier to noise ratio (C/No) [3], [4]. The latter can be used to create a null in the radiation pattern in the direction of an anticipated interferer. The beam/null steering can be accomplished by using the appropriate algorithm that will feed the appropriate voltage and phase levels to the antenna array elements to steer the beam or create a null in the direction of interest.

Utilizing the high gain, directivity, and beam steering capability of antenna arrays into the design of flying UAV structures is very attractive for several reasons such as:

1) This will provide the flying UAV the capability to transmit at higher data rates.
2) An antenna array will extend the range of communication to the UAV (increase communication distance).
3) Re-use of structural components as radiators can:
   - Reduce weight.
   - Reduce drag.
   - Lower manufacturing costs.
   - Make system more robust by eliminating external components that can be damaged by user or during take offs/landings.
4) Beam steering will provide a better communication channel via the ability to "null out" interfering sources, hide the information from enemy areas and direct the transmission to the ground station location.

Although the utilization of antenna arrays in UAVs has been present in some literature, none of them investigated the integration of such arrays as a part of the mechanical structure of the flying UAV or re-used any as radiating elements. Also, limited number of previous work focused on the use of beam steering to enhance the communication quality, the range as well as the transmission data rates. Most of the literature covers a specific design/application of a UAV [5]-[6].

In [7], a dual band T-shaped monopole for WLAN operation in the 2.4 GHz and 5 GHz bands was proposed. The design occupied a 64.5×75 mm\textsuperscript{2} area including the GND plane. An L-shaped monopole with dual band operation was proposed in [8] which occupied an area of 44.1×50 mm\textsuperscript{2}. Other implementations have been proposed in literature, but none is suitable for this application because of the size limitation.

In this work, we present a linear antenna array embedded within the wing structure of a small UAV that consists of 4/8-monopole antenna elements. The miniaturized monopole antenna used in this work is a derivative of the T-shaped monopole presented in [7], but with a much smaller size that fits well within the UAV wing as part of its structure (we call it an L-shaped Monopole). The antenna is designed to operate in the 2.4 GHz frequency band for operation within a WLAN/ZigBee framework.
The paper is organized as follows; Section II provides the modeling and design of the linear antenna array as part of the wing structure for a small UAV. Section III presents and discusses the simulation and measurement results. Finally, Section IV concludes the paper.

II. MODELING OF PRINTED EMBEDDED ANTENNA ARRAY

A printed monopole on a 0.8 mm FR-4 substrate with $\epsilon_r = 4.8$ was used as the basic radiating element for the array. It is to replace a similar shape wing-slot as shown in Figure 1, thus having a structural component as a radiating element. The wing-slot is the basic element within the wing structure of a small UAV. The mini-Telemaster UAV (Figure 2) used in this work has a wing span of 114.3 cm (45 in.) and a total of 18 wing-slots. The fuselage length is 82.6 cm (32.5 in.). The UAV is made of balsa wood ($\epsilon_r = 1.2$).

The L-shaped monopole has a long arm ($MS_L$) and a short arm ($Arm$). The ground plane was placed on the opposite side of the wing-slot (opposite to the antenna) and had a length of ($GND_L$) from the center of the feeding center hole ($r$). The length of a single wing-slot is 15.2 cm and its height is 2.08 cm. The inter-wing-slot spacing is 6.5 cm. The printed embedded antennas are to be fed using RG-316 coaxial cables through the center holes. The voltage and phase excitations are assumed to be obtained from the control unit within the UAV fuselage.

A single element wing structure was modeled using a full wave Method-of-Moments (MoM) 3D field solver (FEKO$^TM$) [9]. The values for the return loss ($S_{11}$) and gain pattern were obtained and stored. Also, a 4-element array was created in FEKO$^TM$. The single element simulation results were passed to MATLAB$^TM$. A script that performed the array pattern multiplication (APM) was used to create the 3D directive gain patterns based on phase excitations. The total gain was obtained using:

$$Gain_{Total} = AF \times Monopole_{3D-Gain}$$

(1)

where $AF$ is the linear array factor, and the $Monopole_{3D-Gain}$ is the 3D gain pattern obtained from the FEKO$^TM$ simulations for a single wing slot antenna. The $AF$ is computed for a specific phase as:

$$AF = \frac{\sin (N\psi/2)}{N \sin (\psi/2)}$$

(2)

where $\psi = kd\cos (\theta_0) + \beta$, $k$ is the wave number ($\frac{2\pi}{\lambda}$), $d$ is the inter-element spacing, and $\theta_0$ is the beam steering angle. The feeding excitation phase values were stored in a look-up table and passed to MATLAB$^TM$ and FEKO$^TM$. The amplitudes were equal. The progressive phase values were computed from:

$$\beta = [-1.06\pi] \cos (\theta_0)$$

(3)

III. RESULTS AND DISCUSSION

The array pattern multiplication within MATLAB$^TM$ was used to save the simulation time that FEKO$^TM$ requires for this large structure (17.5 hours for a single frequency with radiation pattern calculation for a 4-element array on a 4 GB RAM server), and to compare results for the 4-element array structure. The designed L-shaped antenna has $MS_L = 33.5$ mm, $Arm = 7$ mm and the GND plane on the bottom layer $GND_L$ extended to 17.5 mm from the center of the through hole ($r = 3.5$ mm).

The embedded antenna designed occupied 20.8$\times$38 mm$^2$, which demonstrate a 65% reduction in size compared to those in [7], [8]. The simulated and measured return loss (RL) are shown in Figure 3 for the 4 antenna elements separated with a 6.5 cm air gap as in an actual wing structure of a small UAV. Notice that the RL of the first antenna suffers from large ripple values, this is due to the passage of 3 RF feeding cables through the hole of the first element which is only 3.5 mm in radius. This made the outer GND shields to come closer to the feeding pin of element 1. Table I shows the measured and simulated return loss, center frequency and 2:1 bandwidth. Figure 4 shows the embedded array within the wing structure of the UAV. The simulated 3D gain pattern of the L-shaped embedded monopole is shown in Figure 5. It is interesting to observe that the donut shape covers the area around the single
Fig. 3. Simulated and measured Return Loss of the L-shaped embedded Monopoles.

Fig. 4. Simulated and measured Return Loss of the L-shaped embedded Monopoles.

wing slot, i.e., the x-z plane (elevation plane).

Figure 6 shows the 2D gain pattern using APM for a single simulation of 4-element and 8-element array with a beam towards the angle $\theta=45^\circ$. The progressive phases were calculated using (3). The uniform linear array embedded within the wing structure has its $\theta = 0^\circ$ at the tip of the wing when placed parallel to the ground (z-axis in Figure 1). Thus a $45^\circ$ beam will focus the beam towards the lower left corner of the wing. This will improve the radio link by focusing the beam towards the clear sky.

The behavior of the antenna array in terms of the half power beam width (HPBW) and side-lobe-level (SLL) for both the azimuth ($\phi$) and elevation ($\theta$) planes has been investigated. Figure 7 shows the simulation results from the uniform linear antenna array using 4-elements for both $\phi=0^\circ$ and $90^\circ$, using APM and $\phi=0^\circ$ using MoM. It is obvious that HPBWs are comparable between $40^\circ$ and $140^\circ$. The SLL was much lower in the MoM simulations because of the actual coupling effects that are taken into account in such a model. The APM shows a consistent SLL of about -11dB in the region of $60^\circ$ to $120^\circ$. For lower elevation angles, the main beam was barely there, and it was focused towards the $\theta = 0^\circ$ and $\theta = 180^\circ$, respectively. In an actual flying environment, this limitation is acceptable (when it occurs during UAV turns, etc.). Figure 8 shows the HPBW and SLL for both the 4-element and 8-element antenna arrays at $\phi=0^\circ$. At least 10$^\circ$ of lower HPBW and 2 dB of lower SLL for the 8-element antenna array was obtained. This means that the beam will be more directional with more rejection at the side-lobes. This follows the predictions from the behavior of uniform linear arrays. To minimize the SLL further, a non-uniform amplitude scheme like the Dolph-Chebychev method can be employed at the expense of lower directivity.

The measurements of the embedded array in terms of gain patterns, beam forming capability, HPBW and SLL will be presented in a following paper.

| $f_c$ (GHz) | $|S_{11}|$ (dB) | BW (MHz) |
|------------|----------------|----------|
| element 1  | 2.4225         | -20.23   | 350.00 |
| element 2  | 2.4450         | -40.38   | 323.12 |
| element 3  | 2.4000         | -21.42   | 278.09 |
| element 4  | 2.4525         | -27.96   | 345.54 |

image beam at $\theta=-45^\circ$ is an inevitable consequence of using linear antenna arrays, and it will be directing above the wing (towards the clear sky).

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IV. CONCLUSIONS

Embedded antennas within wing structures for small UAVs are very attractive. The use of embedded antenna arrays will increase the range and data throughput thus will allow for high quality video transmissions. We have presented the design and performance of a fabricated small size embedded monopole antenna operating at 2.4 GHz. Two linear antenna arrays of 4 and 8-elements were modeled, simulated and compared in terms of the HPBW and SLL to access the performance of the linear array as part of the wing structure of a small UAV.

ACKNOWLEDGMENTS

This project has been partially funded by the Michigan Space Grant Consortium (MSGC), USA. The first author would like to thank EM Software and Systems (EMSS) for providing the simulation tool FEKO\textsuperscript{TM}, as well as KFUPM for its continuous support for research projects.

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