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Electronic Leashing of an Unmanned Aircraft to a Radio Source

Cory Dixon, and Eric Frew, *Member, IEEE*

Abstract—**This paper presents a solution to the radio leashing problem in which an autonomous aircraft is electronically tethered to a radio node in order to maintain a communication link between them. The solution presented here solves the leashing problem using only local measurements of the communication link and assumes no knowledge of the radio node location or on the RF propagation environment. In this work, the signal-to-noise ratio for each individual link is the only input into a high-level steering control algorithm.**

I. INTRODUCTION

Unmanned aircraft offer a significant advantage over manned aircraft in missions that are often characterized as "dull, dirty, and dangerous" [1]. One example mission is the use of a UAV as a "bent-pipe" communication channel [2-4]. In areas where communication infrastructure is damaged or non-existent and satellite coverage is unavailable or costly, a UAV can be configured as a flying wireless access point to provide communications services.

The leashing problem, originally presented by the authors in [5], is to electronically tether a UAV to a radio source so that a desired level of communication performance is maintained between the radio source and the UAV. This problem is of interest in many UAV applications such as in situ sensing where communication is required between small wireless nodes that would otherwise not be able to communicate to a remote ground station because of range constraints or line-of-site obstructions.

Applications of interest to this work are the deployment of wireless sensors in the Artic ice caps by UAVs and the use of UAVs to study tornado formation [4]. In the Artic mission, the sensors are to be deployed and left to drift on ice shelves and in the Artic Ocean to collect environmental data over several days such as sea surface temperature, ocean currents and ice flows. Due to the remote location of the sensors and their small size, ground based communication to the sensors is not feasible. After deployment of the sensors by the UAV, it will act as a communication relay, collecting the information stored in the sensor for later downlink to a remote ground station. Since the sensors will be left to drift with the ocean currents and ice flows, it is not expected that the UAV will not have accurate knowledge of their location at all times. Thus, there will be times that the UAV will need to track down a single wireless sensor knowing only estimates of the location of the sensor. Once the UAV is in communication range, it should maintain a flight pattern that provides a solid, strong communication link to the sensor until the data logged by the sensor is collected by the UAV.

A second application is to aid in the study of tornadogenesis by utilizing UAVs to measure pressure, temperature, and humidity as well as hydrometeor types, amounts, and concentrations at the base of the cloud layer. Because of the dangers associated with the severe thunderstorms that produce tornadoes, placing a manned aircraft in this region is not an option. To aid in the volumetric measurement of the storm, some UAVs will be capable of deploying sonde-like sensors that will drift with the wind currents in the storm, telemetering data over a wireless network while other UAVs will have the mission of autonomously maintaining positions that optimize communications between all data-gathering platforms in an ad hoc network.

This paper proposes using the signal-to-noise ratio (SNR) of the communication link as the primary input to a steering control algorithm used to leash the aircraft to a radio source. To solve the leashing problem, two different controllers are presented: constant SNR orbit, and maximum SNR gradient ascent. The two controllers are needed to accomplish the two primary phases of the leashing problem.

When the UAV is assigned to communicate to a specific sensor, the first task of the UAV will generally be to head towards the transmitter to increase the SNR to a desired value. In this phase of the task, the maximum SNR gradient ascent controller is used to follow a path that maximizes the measured gradient of the SNR field, which results in a direct path towards the transmitter. Once a desired SNR is reached, the constant SNR orbit controller will put the plane in orbit about the node to maintain a desired SNR.

II. RELATED WORK

The leashing problem was first introduced by the authors in [5] and presents the fundamental ideas of electronic (or radio) leashing. This paper examines in detail the gradient ascent and constant SNR controllers.

The concept of tracking a SNR level curve with a UAV using a steering control law is essentially a path-tracking problem for nonholonomic vehicles similar to that presented in [6, 7]. However, Bulluchi *et al.* assume that the vehicle has knowledge of the cross track and heading angle errors to generate a steering control law that has three discrete outputs: full left turn, straight, and full right. Though this type of controller is optimal in generating the shortest path route, it is in general not desirable to use due to chatter that

C. Dixon is a PhD candidate within the Aerospace Engineering Department, University of Colorado, Boulder, CO 80309 USA (e-mail: cory.dixon@colorado.edu).

E. Frew is an assistant professor with the Aerospace Engineering Department, University of Colorado, Boulder, CO 80309 USA (e-mail: eric.frew@colorado.edu).

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results from the use of a bang-bang style controller.

Similar work in contour following and gradient ascent for multiple, cooperative vehicles in a sampled environment is presented in [8, 9]. Though it is of interest for future research, multiple cooperative UAVs is not considered in this work.

III. Background

For this paper, it is assumed that the UAV has an on-board avionics system that maintains airspeed and altitude while tracking a commanded turn rate. In addition, the radio on the leashed UAV is capable of collecting information on the communication link such as throughput and signal-to-noise ratio. Because of the known, continuous motion of the UAV, information about the structure of the SNR field can be obtained and used in addition to the singular SNR measurement.

A. UAV Motion

The UAV is assumed to follow the Dubin's car model [6], traveling at a constant speed and altitude with a bounded turn rate. In this system, a UAV at any time t can be specified by its coordinates ($x(t)$, $y(t)$, $z(t)$, $\psi(t)$), where x and y represent coordinates a Cartesian reference frame attached to the radio node, z is the height of the vehicle and ψ is the heading angle of the aircraft. The motion of this system is governed by the following equations

$$\begin{aligned} \dot{x} &= V_T \cos\psi \\ \dot{y} &= V_T \sin\psi \\ \dot{\psi} &= u \end{aligned} \tag{1}$$

where V_T is the forward speed and u is the control input and due to vehicle dynamics and control system constraints is bounded to $|u| < \omega_{\max}$. For an aircraft in a coordinated turn, the maximum turn rate is limited by the maximum bank angle that the aircraft is allowed to achieve as given by

$$\omega_{\max} = \frac{g \tan\beta_{\max}}{V_T} \tag{2}$$

where g is Earth's gravitational acceleration constant and β_{max} is the maximum roll angle allowed by the autopilot system.

Let $\vec{x}_i$ represent the positional vector of the UAV at time index i. Then the discrete versions of (1) are found by integrating the equations for a constant turn rate $u_i \neq 0$ over the time interval $t_0 < t < t_0 + T$ such that the change in position over a time step from $\vec{x}_k$ to $\vec{x}_{k-1}$ as a function of time T and control input u is

$$\Delta\vec{x}_k = \vec{x}_k - \vec{x}_{k-1} = \frac{V_T}{u_k}\begin{bmatrix} \left(\sin(Tu_k + \psi_{k-1}) - \sin(\psi_{k-1})\right) \\ \left(\cos(\psi_{k-1}) - \cos(Tu_k + \psi_{k-1})\right) \end{bmatrix} \tag{3}$$

For brevity, the kinematic equations for when u=0 are not presented.

B. SNR Model

For any two wireless nodes i and j, let $\vec{r}(\vec{x}_i, \vec{x}_j) = (\vec{x}_j - \vec{x}_i)$ represent the position of node j w.r.t node i. Then the power received at node j from i's transmission can be modeled by the standard empirical model in decibels as

$$P_j(\vec{r}_{ji}) = 10\log\left(K_{ji}(\vec{r}_{ji})\right) - 1o\alpha\log\left(\left\|\vec{r}_{ji}\right\|\right) + F \tag{2}$$

where $\alpha > 2$ is the exponential decay of the signal ($\alpha = 2$ is the ideal propagation model in free space) and $K_{ji}(\vec{r}_{ji})$ represents the directional gain of the link and is dependent upon the gain patterns of each antenna, the orientation of direction between the two, the transmitted power, and the quality of the radio electronics used by each node. F models the random variation of the received power due to Shadow fading and has a Gaussian distribution.

The noise $N_j(\vec{x}_j)$ that a receiver has on its input is dependent upon the quality of the receiver electronics, the noise temperature of the system, and the local RF environment of the node. The signal-to-noise ratio at node j of i's transmitted signal, given in decibel form, is

$$SNR(\vec{x}_j, \vec{r}_{ji}) = P(\vec{r}_{ji}) - N_j(\vec{x}_j) \tag{5}$$

The noise, as presented here in decibels, can also include affects from jamming such as in the case a node becomes faulty and continuously transmits on the channel.

There are several advantages to using the SNR instead of other locally measurable metrics such as received power or throughput, or even GPS position. Mainly, the SNR provides a robust indicator of the available bandwidth and quality of each link, even in the presence of non-uniform disturbances that may be due to noise or line-of-sight link obstruction. Another significant advantage is the fact that an SNR measurement does not require any additional communication than what is already required between the UAV and wireless node, leaving the limited bandwidth of the communication link to be used for the download (upload) of mission critical data.

The well-known Shannon-Hartley theorem [10] states that a wireless communications channel has a maximum rate at which information can be cleanly transmitted and is given as

$$C = B\log_2\left(1 + S/N\right) \tag{6}$$

where C is the Shannon capacity in bits per second, B is the bandwidth of the channel in hertz, and S/N is the signal-to-noise ratio of the communication signal expressed as a straight power ratio (not as decibels). Because the available throughput is directly related to the S/N, the objective of the leashing control scheme to maintain a constant S/N of the communication link is equivalent to maintaining a desired bandwidth capability of the communication link. For the rest of the paper, SNR will be used to represent the signal-to-noise ratio field, S is a measurement of the SNR in decibels, and S/N is used to represent the power ratio.

Since the Shannon-Hartley theorem provides a theoretical maximum, independent of hardware and coding scheme, an empirical piecewise model of a realizable throughput versus SNR is presented in [11] to model hardware and encoding affects. Thus, even though a specific wireless communication system is not being modeled, only a calibration of the system is required to determine a desired SNR for which to track in the constant SNR orbit to maintain an achievable throughput value of T.

C. Path Gradient

Because of the continuous motion of the UAV, information about the structure of the SNR field can be obtained and used in addition to a singular measurement S. For this work, the path gradient is generated for the link and is the parameter that directly generates the turning rate control for the gradient ascent algorithm

At a time t, the UAV (node j) receives a transmission from node i and measures the SNR to be $S(t) = SNR(\vec{x}(t), \vec{r}_i(t))$, where the index j has been removed. At the next communication time $t+T_c$, the SNR is measured to be $S(t+T_c)$. The time rate of change of this signal is related to the path of the UAV and the location of the UAV within the SNR field. In continuous time, the time derivative of $S(t)$ from the UAV motion in the direction of motion, known as the path gradient, and is given as

$$\dot{S}_P = \left\langle \nabla S(\vec{r}_i), \dot{\vec{x}} \right\rangle \frac{\dot{\vec{x}}}{V_T} \tag{7}$$

where <,> is the inner product and $\nabla S(\vec{r}_{ji})$ is the vector gradient of the SNR field. Since the UAV collects the SNR measurements at discrete times, it is of interest to understand how the sampled positions affect the actual measurements. Thus, (7) can be modeled in discrete time using a backward difference approximation to obtain the relation of the measured change in S to the gradient vector of the field

$$\Delta S_k = \left\langle \nabla \bar{S}_k, \Delta \vec{x}_k \right\rangle \tag{8}$$

where $\nabla \bar{S}_k$ is some average of the gradient vector over the positions of the node at time k and k-1.

IV. Turning Rate Controllers

For the controllers presented below, the only input into the system is the measured SNR and the only output is a turn rate command. Since the controllers only operate only the received SNR, and not on position and range, assumptions of communication range, RF propagation environment, and antenna orientation are not needed. Without these assumptions, the exact position of a sensor does not need to be known. In addition, since the controllers only use the received signal-to-noise ratio, these controllers do not require any additional communication specifically for the control system than is already present in the network.

Since the controllers presented below uses the differences of the error signal, measurement noise of the SNR becomes important. Thus, a suitable filter is required on the SNR signal measurements to remove high frequency content that will be present due to shadow fading, F, given in (4).

A. Maximum SNR Gradient Ascent

In this controller, the goal is to direct the UAV to fly along the direction of maximum gradient of the SNR field. This controller is used in the initial phase of the leashing problem, when the UAV is first assigned the task, since in general the UAV will not be near the nodes of interest. Thus, the current SNR will be small and the UAV will need to fly towards the desired SNR. This controller thus drives the UAV in an optimal direction towards the nodes. As the UAV approaches the desired SNR, then the controller is transitioned from the maximum gradient ascent to the constant SNR orbit controller.

This controller is separated into two phases: maximum gradient search, and maximum gradient ascent. In the search phase, the UAV attempts to measure and determine the maximum gradient vector. Once an estimate of the value and direction of the gradient is found, the controller switches to the second phase to fly the plane along the gradient. In the maximum gradient search phase, the UAV flies in circles, specified by a predetermined turn rate until the maximum change in the SNR, ΔS_{max}, is obtained. It is assumed that when the ΔS_{max} is found that the direction of motion and that of the gradient vector are aligned so that $\Delta S_{\max} = \|\nabla \bar{S}_k\| \cdot \|\Delta \vec{x}\|$.

When the maximum value is found, the UAV switches to the gradient ascent phase. In this phase, the controller generates the output based on an estimate of the angle between the maximum gradient direction and the current heading. Since the path gradient involves the dot product, an angle between the direction of maximum gradient and the direction of travel can be found from (8) and is given as

$$\psi_e = \cos^{-1}\left(\frac{\Delta S_i - \Delta S_{\max}}{\Delta S_{\max}} + 1 \right) \tag{9}$$

Due to the nature of the problem, only positive values of the angle error are obtained from this formula. To make this a proper error function for the controller, directionality must be determined for ψ_e. The directionality of the error, Φ, is found by using the direction of the control over the last few time steps as well as the change of ψ_e over the past few steps so that $e_k = \Phi \psi_e$. The pseudo code is given in Fig. 1.

```
psiE_i ⇒ angle error from deltaS_i
phi ⇒ direction of psiE_i
deltaPsi_i = psiE_i-psiE_i-1
if( controlSwitch == 0 & deltaPsi > 0)
    controlSwitch = 1;
    if(u_i-1 - u_i-2 > 0)
        phi=1
    else
        phi=-1
    end;
elseif( controlSwitch == 1 & deltaPsi < 0 )
    controlSwitch = 0
end
```

Fig. 1. Pseudo code used to determine the sign of the angle error, Φ.

A discrete PID controller is used to generate the control input based on and is given as:

$$u_k = K_1(e_k) + K_2(e_k - e_{k-1}) + K_3(e_k - 2e_{k-1} + e_{k-2}) \quad (10)$$

where $K_{(.)}$ represents the gains on the error input. Though the difference equation above can be simplified further into a discrete transfer function, the control law is presented in the form of (10) in an attempt to maintain some physical meanings to the gains of the controller to aid in the selection of the gains.

Again, this controller is presented in the application of a single UAV and a single node. By modifying the measured SNR to be the additive sum of the SNR collected from nodes of interest, the controller well follow the maximum gradient contour of the combined field. When the UAV is far from all nodes of interest, the gradient direction will be towards the center of the nodes. As the UAV comes close to a node however, the gradient ascent will look to climb this peak. Thus, this controller should only be used for multiple nodes when it is sufficiently far away. As the UAV approaches the chain, then the Equalizing SNR controller will be used.

B. *Constant SNR Orbit*

The goal of this controller is control the motion of the UAV to maintain some desired SNR from a specified radio source. Tracking a level curve of the SNR field is equivalent to driving the time derivative of the measured SNR along the UAV path to zero. From (7), this is only possible when the UAV is flying a path perpendicular to the gradient vector.

To drive the UAV along a specified SNR level curve, an error signal:

$$e_k = S_k - S_d \quad (11)$$

is used in a digital controller. The error signal at time step k is simply the difference of the measured SNR value, S, to the desired SNR value of S_d. The discrete controller used to generate the steering commands to drive the UAV along a path defined by S_d is:

$$\begin{aligned} u_k &= F_1 u_{k-1} + F_2 u_{k-2} + F_3 u_{k-3} + K_1(e_k) + K_2(e_k - e_{k-1}) \\ &\quad + K_3(e_k - e_{k-2}) + K_4(e_k + 2e_{k-1} - e_{k-2}) \end{aligned} \quad (12)$$

where $K_{(.)}$ represents the gains on the error input and $F_{(.)}$ are the gains on the previous control output. The gain K_1 acts as an integrator for the controller on the error function since it is the only place where S_d has a direct affect the control output. Thus, by choosing large K_2, K_3, and K_4 and a small K_1 will lead to a controller that will begin to follow a SNR level curve and over time spirals towards the desired SNR value.

The controller as presented will cause the airplane to follow an orbit about the radio node in a clockwise manner (i.e. a negative turn rate in the simulation environment) when all positive gains are used. This is because of the form of the error differences that are used. For example, when the UAV is far from the desired SNR value, the error term, e_k will be negative causing the plane to turn to increase the turning rate in the negative direction.

Though this controller assumes only a single transmitting node, the controller can be made to orbit two closely spaced nodes by adding the measured SNR from each node and using the combined value as input into the controller. The controller will then follow the combined SNR contour. The main difference is that the contours are no longer necessarily circular. Depending upon the node spacing and the desired SNR, the contour can go from an oval to a figure-8. Since the combined field will allow the UAV to be closer to one node (higher SNR) than the other, the communication performance to the farther node will be degraded slightly.

V. Simulation and Discussion

Simulations of the above controllers have been implemented to study their behavior and to gain some insight into possible changes or improvements of the controllers. In the initial simulations that have been performed, only a single UAV has been used with multiple transmitters.

In the simulations, the UAV is chosen to model the Ares UAV [12] and the radio characteristics are taken from measurements made of an 802.11b wireless node used in operation of the Ares UAV in the AUGNet project. The specific values used for the UAV model are a flight speed of V_T = 25 m/s, with a bounded turn rate of ω_{max}=0.22 rad/s, from (2), due to a limited bank angle of 30°. In the simulation the radio propagation model given in (4) is used where α = 3.5, K_0 = 1 W/m^2 and $N_j(\bar{x}_j) = N_0 + J(\bar{x}_j)$ where N_0 = 1e-5 W and $J(\bar{x}_j)$ represents noise seen by the UAV at its current position due to the local environment due to a faulty radio so that $J(\bar{x}_j) = P(\bar{r}_{jl})$, where l is the index to the faulty node.

Initially, a transmitting node is placed at the origin of a 1 km x 1 km simulation environment, shown as the blue circle in Fig. 2. A second transmitter is placed at x=200 m and y=200 m and acts as a faulty transmitter that continuously transmits on the wireless channel, thus acting as a noise source (shown as red circle). This causes the contour lines of the SNR field to change as shown in Fig. 2. In the plot, the contour lines are shown as a dashed-dotted line for SNR contours for every 100 m range from the transmitting node. The desired SNR for which to orbit the node at is indicated in the figure as the red contour.

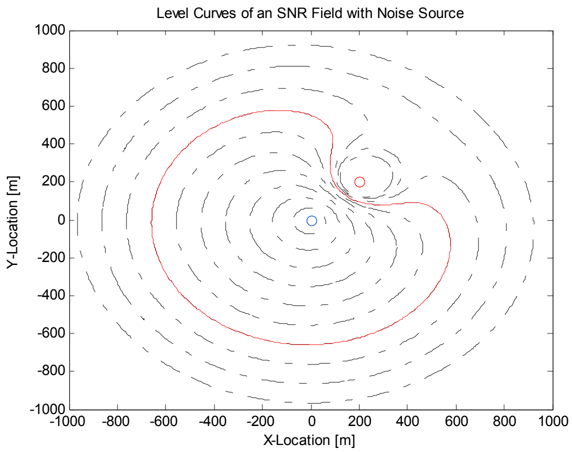

Fig. 2: Level curves of an SNR field with a faulty wireless node acting as a noise source.

From Fig. 2 it can be seen how a position only based solution to orbiting a communication node may fail in maintaining a solid communication link. If a position based solution was used to orbit the node at the distance determined a priori by the desired SNR, then when a noise source is present, the position-based solution will fly directly over the noise source, causing a degradation of the received SNR and possible communication loss if the noise source is strong enough.

A. Maximum Gradient Ascent

The path of the gradient ascent algorithm is shown in Fig. 3 for two different simulation runs. Though not explicitly obvious in the figures, the simulation environment for both runs is the same as above The two phases of the controller can be seen in the image. Again, the first phase of the controller is to simply orbit until the maximum gradient has been measured. The second phase then begins, using this number to determine a heading angle error. The initial location of the UAV is indicated by an 'x' and the final location at the end of the simulation is marked by an 'o'.

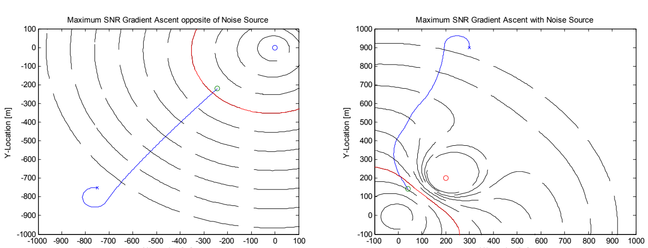

Fig. 3. Maximum gradient ascent paths for two simulation run. On the left, the UAV was placed so as to not see the affects of the noise source while the right plot shows the track in the presence of noise.

The path of the UAV in the gradient ascent shows that with the gains used in this simulation that the UAV holds the orbit for a bit too long after measuring the maximum gradient. However, the UAV follows a smooth, straight path along the maximum gradient of the SNR field.

An interesting scenario is when the UAV flies in the near presence of the noise source shown in the right of Fig. 3. In this case, the assumption of a single maximum gradient is violated and the geometry of the angle error becomes invalid as the UAV gets closer to the noise. Thus, when the UAV enters the region dominated by the noise source the controller no longer has a proper angle error. Though not shown, eventually the UAV goes off track causing the controller to revert to phase 1, finding the maximum gradient direction. Since the new maximum gradient direction is found close to the noise source, the UAV again tracks the path of maximum gradient finally flying directly over the node of interest.

Analysis of the path chosen by the ascent algorithm suggests an immediate change in the coding of the algorithm. In this simulation, only in phase 1 of the controller does the UAV measure, or update, the maximum gradient value. In phase 2, the controller simply uses the value obtained in phase 1 without regard to local disturbances that will affect this value as shown above. To account for local disturbances, the maximum gradient value should be continuously updated in phase 2 of the controller. Further research is needed to determine the proper update algorithm. However, even with the local disturbance the UAV is still able to ascend the SNR field to the desired SNR contour.

B. Constant SNR Orbit

To gain insight into response of the constant SNR controller after switching modes from the ascent controller, the UAV was randomly initialized in the simulation environment with no noise source initially present. The response of the controller is shown in Fig. 6 while the path of the UAV is shown in Fig. 5. Figure 5 shows that the controller is able to track the given level curve. The trace of the UAV path shows the results, as discussed above, of choosing a K_I to be small as compared to the other gains in that the UAV begins to track the shape of the level curves initially and slowly spirals outwards to S_d.

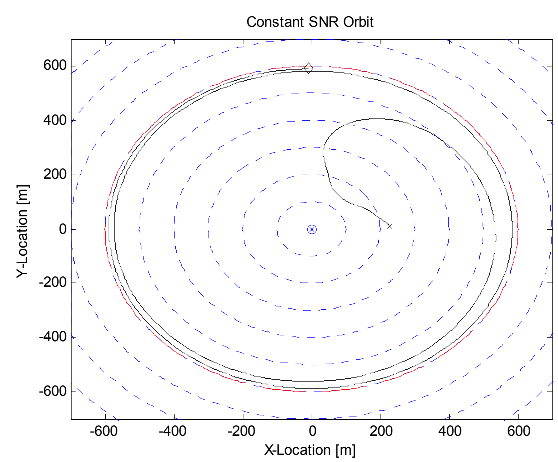

Fig. 5. Typical path followed by UAV using the constant SNR orbit controller to orbit a radio node without the presence of a concentrated noise source.

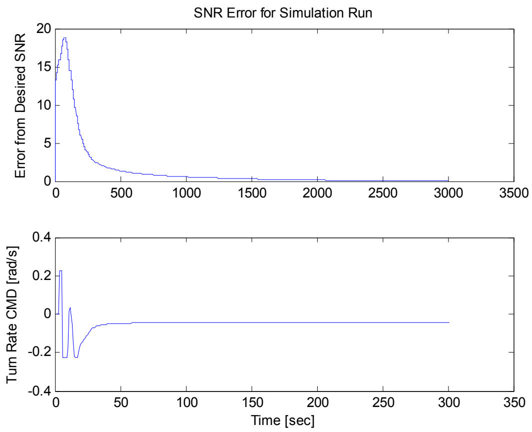

Fig. 6. SNR error and turning rate command output for constant SNR orbit shown in Fig. 5

The top plot in Fig. 6 shows that the controller does drive the error signal to zero and that for the gains used in the simulation a smooth turn rate command is generated as shown in the bottom plot. This bottom plot shows a significant advantage over the bang-bang style controller used in [7] in that the turning rate settles to a known constant value, as one would expect to occur since the UAV is tracking a circular path in this case. This is not possible with the bang-bang controller, resulting in undesirable chatter.

In Fig. 7, the track of the constant SNR controller is shown when a concentrated noise source is present.

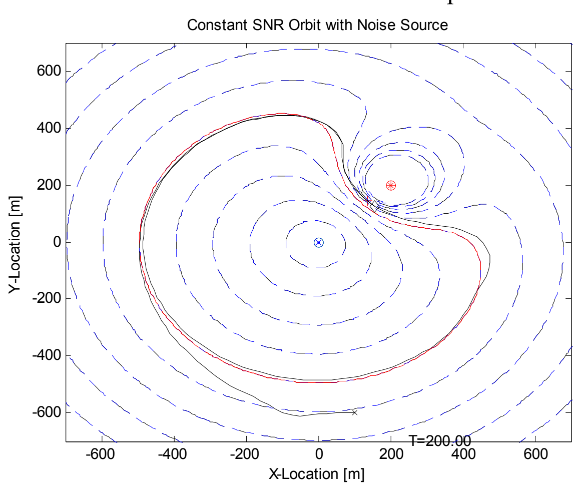

Fig. 7. Path followed by UAV using the constant SNR orbit controller to orbit a radio node in the presence of a concentrated noise source.

It is seen in the plot, that even in the presence of the noise source that the UAV, using the constant SNR controller, is able to track a level curve of the SNR field maintaining a solid communications link with the wireless node. If a position-based controller had been used, then the UAV would have flown directly over the noise source losing valuable communications bandwidth and quality.

VI. Conclusion & Future Work

This paper presented turning-rate controllers for use on unmanned aircraft to search for and actively maintain a communication link between an UAV and a wireless node. The controllers are adaptive to dynamic noise environments since the controllers do not use the relative position of the communicating nodes directly in the algorithms. In addition, since the controllers only use the received signal-to-noise ratio, these controllers do not require any additional communication specifically for the control system other than is already present in the network. A significant additional advantage of the controllers presented in this paper is generation of a smooth control signal (bounded by the maximum turn rate) that removes the chatter that results in a bang-bang style controller.

Future research work will add additional inputs into the controller such as link delay, power usage, and UAV motion that affect the communication performance and quality. The idea of leashing will also be extended into work on a leashed chain of UAVs. By using the concept of leashing among multiple cooperative vehicles, long-range communications can be autonomously supported by having UAVs act as communication relays.

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