UKAEA-RACE-CP(23)05

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This paper has been submitted to
International Conference on Intelligent Robots and Systems (IROS), Las Vegas, USA, 25-29 October 2020

Optimal Sensor Launching with UAVs for Monitoring of Hazardous Environments

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I. SENSOR DEPLOYMENT WITH UNMANNED AERIAL VEHICLES

Wireless Sensor Networks (WSN) have been shown to improve data gathering processes over large spacial and temporal scales at a low cost [1], as well as the automation of decision making processes in complex industrial settings [2]. The nuclear sector is no exception to this, being obvious applications structural health monitoring [3] and radiation monitoring [4]. While the greatest level of integration of such systems can be achieved during reactor construction, the nuclear energy field has an abundance of research or legacy reactors that need to be fitted with such systems as deemed necessary. The use of Unmanned Aerial Vehicles (UAVs) for such tasks is unintrusive and safe, as it can be performed remotely, and has been successfully demonstrated for different applications [5]–[7]. Here, we further propose the deployment of said networks in cluttered environments by launching the sensors from on-board a UAV towards desired targets. This method was first proposed for cluttered environments in [8] and we hereby expand on the subjects of sensor trajectory modeling and clutter-aware optimal trajectory planning. This method is shown to be robust to clutter using minimal perception and computational power, making it ideal for use in cluttered environments where the usage of large aerial manipulators is not possible. Further contributions from this work are the real time calculation of accurate sensor launching trajectories and a method to make these trajectories invariant to the launched payload.

II. NUCLEAR FUSION USE-CASE

Nuclear environments are some of the most hazardous environments in the world, driving the need for robotics and autonomous applications in the field. This is no different in nuclear fusion, where considerable advances in remote maintenance and inspection are necessary before commercialisation is possible [9]. Serial manipulators, amongst other tools have been successfully used in maintenance of the Joint European Torus (JET), however, as facilities become larger to support larger tokamaks the amount of space that needs to be inspected and maintained grows exponentially. For example, the proposed DEMO active maintenance facility will be used to autonomously maintain the robots that maintain the fusion reactor, and will span 737,000m^3 all requiring remote inspection and intervention for maintenance [10]. The use of UAVs can not only enable the inspection of such locations, but also their medium to long term monitoring, if sensor nodes are deployed. The capacity to launch these sensors is exacerbated when taking into account the dense clutter in these locations, as hazardous flight in close proximity to solid objects is not necessary.

III. ROBUST SENSOR TRAJECTORY PREDICTION

There are two main sources of uncertainty in the trajectory of low Reynolds projectiles such as small sensors. Firstly the drag of the sensor, which is typically a bluff body and thus subject to large variability, incoming turbulence and sensor shape. Secondly, pitch and yaw oscillations have the effect of momentarily increasing drag, leading to shorter ranges than expected, but also to somewhat random deviations from predicted trajectories. The accurate prediction of such trajectories would normally be achieved by fully characterising projectile aerodynamics by numerically solving the Navier-Stokes equations, or by performing wind tunnel experiments. However, relying on such computationally intensive methods would limit the variety of usable payloads. To this purpose, we employ a different strategy, where we compromise in accuracy, and aim instead for obtaining similarity in behaviour of various sensor payloads and then deploy reduced order models. The first step towards this objective consists in sizing a tail stabiliser for the projectile such that the half-life of pitch oscillations meet a certain target value. As such, a reduced model where pitch oscillations are neglected can be used, and the resulting excess drag can be empirically estimated. Initial conditions, pitch perturbations and aerodynamic coefficients such as bluff body drag, can also be optimised to better fit experiments. Finally, validation against experiments provides

This work was supported by NERC and NPIF grant NE/R012229/1, and carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. It is also funded by the Engineering and Physical Sciences Research Council (EP/R009953/1, EP/N018494/1, EP/R026173/1, EP/S031464/1); the EU H2020 AeroTwin project (grant ID 810321). The work of Mirko Kovac is supported by the Royal Society Wolfson fellowship (RSWF/R1/18003).

a confidence interval on the trajectory prediction as function of travelled distance and initial conditions.

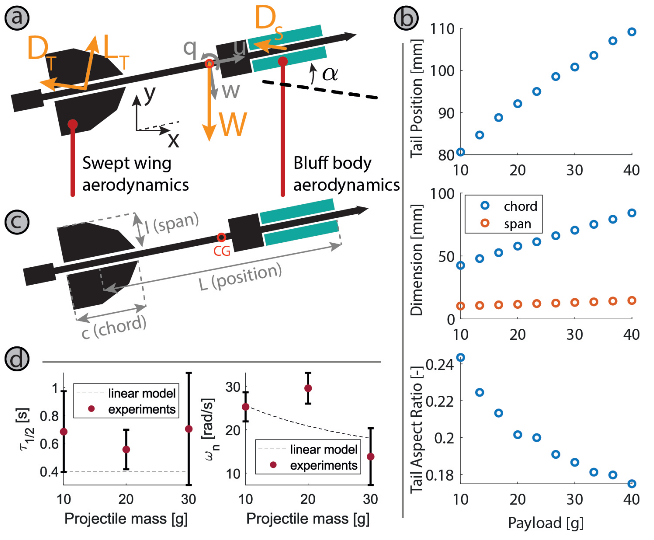

Fig. 1. A. Projectile geometry and applied forces. B. Optimised stabiliser geometry for different payloads. C. Stabiliser geometrical parameters, D. Experimental verification of damping parameters predicted by optimisation problem

The planar dynamics of an object in fight fig. 1.A are given by eqs. (1) and (2). These equations can be linearised in the form of eq. (3), where $\mathbf{A}$ is obtained from the slope of the aerodynamic force coefficients. The oscillatory behaviour of a projectile is then estimated by solving this eigenvalue problem. The longitudinal dynamics of such a projectile are characterised by and (ideally) damped short period mode an no phugoid mode due to the lack of a lift component at zero angle of attack (α).

$$\begin{bmatrix} F_u \\ F_w \\ M_v \end{bmatrix} = \begin{bmatrix} m \\ m \\ I_{yy} \end{bmatrix}_{diag} \begin{bmatrix} \dot{u} + q \cdot w \\ \dot{w} - q \cdot u \\ \dot{q} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \dot{x} \\ \dot{z} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} R \end{bmatrix} \begin{bmatrix} u \\ w \\ q \end{bmatrix} \tag{2}$$

$$\dot{\mathbf{x}} = \mathbf{A}_{4,4} \cdot \mathbf{x} \tag{3}$$

The optimisation problem defined in eq. (4) finds aft tail dimensions that ensure the same oscillatory motion decay for different payload mass and shapes fig. 1b. The design space is in the tail's $(chord, span, position)$, defined in fig. 1c and minimisation is for the relative error to the target half-life, and total mass to payload mass ratio. The system is ensured to be over-damped by applying a lower barrier function (lbf) to the entry in $\mathbf{A}$ (eq. (3)) respective to $\partial C_M / \partial \alpha \xrightarrow{\alpha \to 0} \partial C_M / \partial w$. It's shown in fig. 1d that this exercise is partially successful in ensuring self-similar behavior between projectiles of different masses. The major source of experimental variability is the fact that projectiles are launched at angles between 5 and 80 degrees, which introduces variability in the non-linear terms present in eq. (1).

$$\min \left(\frac{\tau_{1/2(tg)} - \tau_{1/2}}{\tau_{1/2}} + \frac{m_t}{m_p} + lbf(\mathbf{A}_{(3,2)}) \right) \tag{4}$$

Being similarity in pitch oscillations ensured, the pitch DoF is removed, and the projectile can be treated as a point mass subject to drag. Rearranging eq. (1) into tangential ($\dot{u}$) and normal ($\dot{\theta}$) coordinates and assuming $x(t)$ to be invertible, the system of equations 5 is obtained, which is dependent on x instead of t. This has the advantage that the problem can be treated as a boundary value problem (BVP), allowing us to set impact conditions and infer a launch position.

A limitation on the rationale discussed thus far is that the vast majority of viscous drag losses at these Re numbers are not due to the drag term D_0 at zero α, but due to large pitch oscillations. Here, we hypothesise that these oscillations are induced in the trajectory due to the lag between the projectile's inertia and gravity induced trajectory curvature. The term $-\frac{D_\theta \cdot g}{u^2}$ in eq. (5b) is introduced as a drag term proportional to the curvature of the trajectory $\frac{d\theta}{dx}$.

$$\frac{dz}{dx} = \tan\theta \tag{5a}$$

$$\frac{du}{dx} = \frac{\text{-}g \sin\theta - \frac{1}{m} D_0}{u \cos\theta} - \frac{D_\theta \cdot g}{u^2} \tag{5b}$$

$$\frac{d\theta}{dx} = \text{-}\frac{g}{u^2} \tag{5c}$$

IV. OPTIMAL SENSOR LAUNCHING

Considering sensor launching occurs from a UAV in approximately static position, we have 5 dof deriving from the multirotor's pose and the launcher's inclination, for 3 dof constraining the target's position. Even after reducing the problem to the plane, there's an infinite number of possible solutions, however, an optimal problem can be solved in terms of criteria such as placement accuracy, distance to clutter, etc. Here, we simplify this problem by reducing it to 2D, however, the same approach can be used if considerably more effort is taken in clutter detection using more complex sensing and visual processing.

Besides ensuring placement in a desired location, sensor launching in cluttered environments needs to take into account the proximity of obstacles to the multicopter and potential trajectories. Optionally, the size of the target relative to the confidence interval on the trajectory, the impact energy and impact angle to target surface can also be taken into account. Equations 5 are solved as a black-box model and the mentioned objectives and constraints are introduced in the objective function as in eq. (6), and normalised. Where $\mathbf{x_{trg}}$, $\theta_\perp$ and L_{trg}, correspond respectively to the target position, target surface normal and target characteristic dimension.

Taking into account our target facilities in the JET, we consider that we will be targeting mostly either straight walls

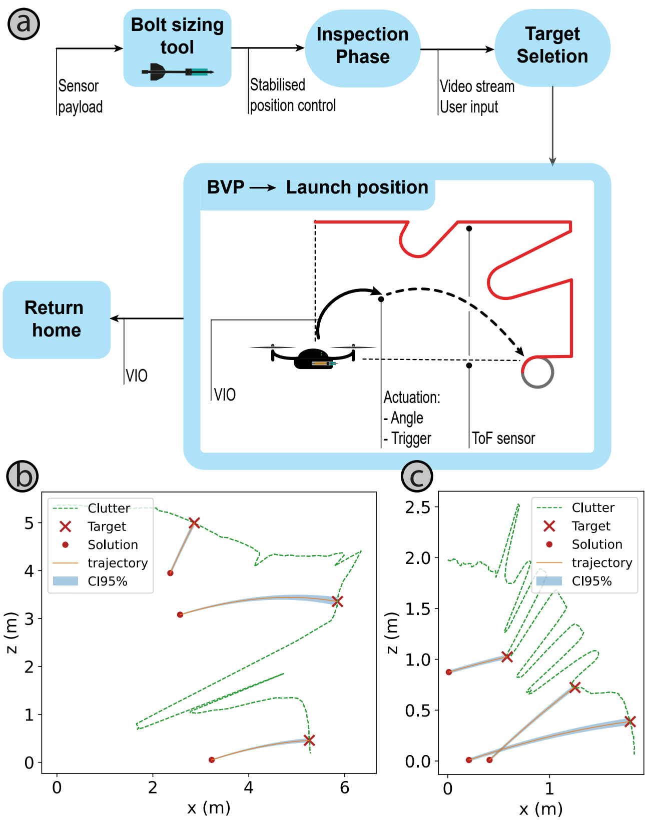

Fig. 2. A. Operations flowchart from selection of a sensor payload operator flight and target selection and optimal launching. B,C. Launch position optimisation results in environments with pipes of ∼10 cm diameter. CI95% corresponds to the 95% confidence interval on the predicted optimal trajectory.

or pipelines between 20 and 50 cm diameter. In order to find which of these cases is in occurrence and which wall/tube best fits the region surrounding the environment, a least squares problem is formulated and the case with lowest residual chosen. These problems are defined with the impact point as the center of the reference frame and thus the first case is defined using a single parameter - the slope angle of a line in polar coordinates, and for the second case two parameters - the center of a circle in Cartesian coordinates. Jacobians are easily calculated from the expressions derived this way.

$$min(||\mathbf{x_i} - \mathbf{x_{trg}}||) \tag{6a}$$

$$min(|\theta_i - \theta_\perp|) \tag{6b}$$

$$\frac{2 \cdot CI_{95\%}}{L_{trg}} \leqslant \epsilon_{trg} \tag{6c}$$

$$\int_0^{\mathbf{x_i}} R_{clutter} - (\mathbf{x} + CI_{95\%})_{\underline{r\theta}}\, d\theta \tag{6d}$$

As equations 5 are defined in space, this problem can be defined in a direct way (3-dimensional optimisation space - $\mathbf{x}$, θ_0) or inverse (2 dimensional space - θ_i, K_{E_i}). Both formulations are solved using global optimisers, because convexity cannot be ensured. Simulations results are shown in fig. 2b,c for real indoors and outdoors scenarios described by data obtained with the on-board sensors.

V. SYSTEM DESIGN

The sensor launcher shown in fig. 3a is based on the one presented in [8], which uses an SMA for actuation of the sear catch, however, the mechanism is updated to have the sear integrated into the spring to facilitate sensor manufacturing. The launcher is mounted on a servo-motor (*DYNAMIXEL XC330-M288-T 2021*) and integrated on a custom 5.1” quadcopter frame. An infra-red time-of-flight sensor with 2° field of view (*TeraRanger Evo 60m 2021*) is mounted on the servomotor and serves both to measure the distance to a target and as a low cost 2D scan for clutter detection in a 2D section plane. The frame is equipped with a self-contained stereo camera (*Intel RealSense Tracking Camera T265*) that performs visual inertial odometry, a PX4 based flight controller (*Pixracer, mRo*) and an on-board computer for system integration *UP-Core-02/32, UP-boards*. Visual feedback is provided to the operator for target selection with an RGB web-camera and laser-pointer mounted on the servomotor.

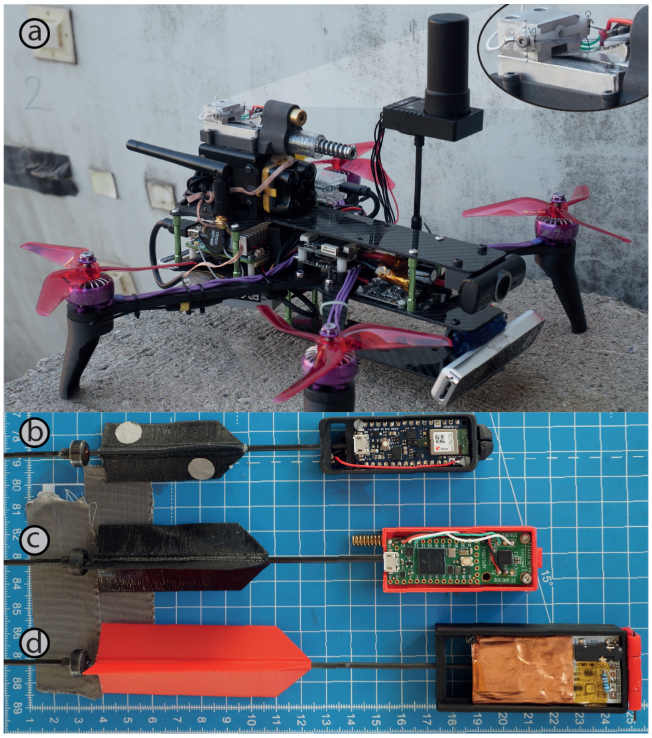

Fig. 3. A. Multicopter and sensor launching system used in experiments. B. 15g sensor for leak detection. C. 21g sensor used in condition monitoring. D. 29g sensor used in radiation monitoring.

Figure 3b,c,d shows several possible sensors developed using readily available prototyping electronics that are within the payload range of the system. These sensors target applications such as leak detection in the reactor’s cooling system, β and γ radiation sensing and condition monitoring. Data forwarding is done via Bluetooth 4.0 (a), local wireless networks (b) or LoRa (c). The tail stabilisers are sized using the method described in section III.

VI. EXPERIMENTS

Sensor launching is an impulsive event that can have adverse effects on UAV flight. However, for the system described in fig. 3, the sensor equates to a maximum of 4% of the total mass, and total impulse of $\sim 10^1$. Figure 4 shows the angular states resulting from sensor launch and that the greatest impact is found on pitch. This effect increases with higher launch angles because the the launcher is placed aft of the CG. Figure 4d shows an exemplary use of the sensor launching system in an indoor environment at a distance of 4 m from the target.

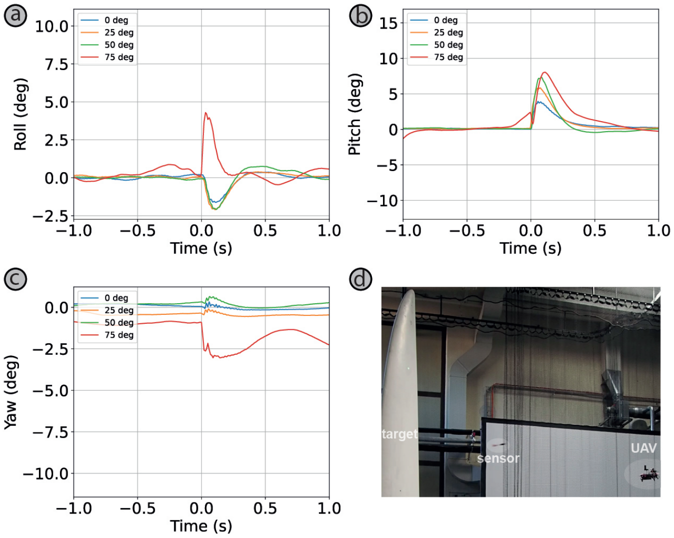

Fig. 4. Angular states of the UAV at the moment of launch and experimental setup of sensor being placed on a structure.

VII. CONCLUSION

We propose here the use of sensor launching as a means for deployment of WSNs in cluttered environments e.g. industrial facilities such as nuclear fusion reactors. While minimal sensing and computational power is used, the system can perform accurate sensor placement, for various sensor payloads. The sensor launching problem is formulated in such a way that impact conditions can be chosen and an optimal launch trajectory chosen taking into account the surrounding clutter.

Concerning projectile similarity of pitch oscillations, improvements can be achieved if a bluff-body wake velocity deficit model is used to predict loss of action of the tail behind the sensor, however, linearisation of such a model is not trivial. Moreover, in terms of using this system in contaminated environments, one must consider radiation tolerance of UAVs which remains mostly unexplored. Sensor attachment mechanisms, such as magnets and adhesives, are sensitive to impact conditions. The method in section IV can partially control these impact conditions, but as this is done as part of a multi-objective optimisation problem, exact impact conditions are not guaranteed. Two approaches can be taken to better control these conditions and should ultimately be combined. The first controls impact conditions by having the sensor enclosure prepared to partially dampen the impact, and the second uses a drawing mechanism that controls the amount of energy stored before launch.

This method is expected to be advantageous in densely cluttered environments as the UAV can maintain a safety distance from obstacles.

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