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Articulated robotic camera design and control

For use in remote control of aircraft

Isabelle Vincent
DRDC Suffield

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Abstract

The Autonomous Intelligent Systems Section, at Defence R&D Canada – Suffield, is developing expertise in unmanned air vehicles (UAV), and is applying remote control technologies to military applications. During trials held in September 2005, using the Silver Fox UAV, some deficiencies of the visual system were observed, and it was concluded that the Silver Fox needs an actuated camera that an operator can orient to investigate suspicious scenes and identify threats. In addition, the ability to use the GPS location of the threat to control the orientation of the camera so that the threat is automatically kept in the field of view as the UAV maneuvers would be extremely useful.

Based on those observations, a pan tilt camera mechanism is designed, modeled, built and controlled. The principle of a robotic arm is studied to design the system. The resulting parallel robot consists of three revolute joints providing motion through a 30˚ vertical arc.

Four different control algorithms were implemented and tested with the robotic camera. First, the system is controlled remotely by an operator to track a specific scene manually. Two other algorithms provide the operator with the possibility to scan an area using joint-space or Cartesian-space trajectory planning. Finally, an adaptation of the Cartesian-space algorithm leads to a GPS waypoint tracking control algorithm. The system inverse kinematics gives the joint position required to orient the camera with the waypoint. By looping continuously through the process, the camera keeps the scene in its field of view with respect to its physical limits.

When the prototype is ready for an aircraft application, the mechanism will need to be optimized to fit the payload limitations of the vehicle and will required design modifications to adapt it to the onboard camera. However, the control algorithms will stay the same, requiring only an adjustment of the system variables.

Résumé

La Section des Systèmes intelligents autonomes de R&D pour la défense Canada – Suffield développe actuellement une expertise dans le domaine des véhicules aériens sans pilote, en appliquant les technologies de téléopération aux opérations militaires sur le terrain. Les essais conduits en septembre 2005, utilisant l'aéronef Silver Fox, ont révélé quelques déficiences au niveau du système de visualisation. Il a été conclu que le Silver Fox avait besoin d'une caméra actionnée de telle manière que l'opérateur puisse l'orienter pour examiner des scènes suspectes et identifier des menaces. De plus, il serait extrêmement utile d'avoir la capacité d'utiliser la localisation GPS d'un site à observer pour contrôler l'orientation de la caméra et garder automatiquement le site dans le champ de vision durant les manoeuvres de l'aéronef.

D'après ces observations, un mécanisme de caméra panoramique et à inclinaison, ainsi que son contrôleur, ont été conçus, et on a étudié le principe du bras robotisé pour concevoir le système. Le robot parallèle qui en résulte consiste en trois articulations à rotule fournissant une trajectoire sphérique couvrant un arc de 30°.

Quatre algorithmes de contrôle sont élaborés et testés avec la caméra robotisée. Le système est d'abord contrôlé à distance pour suivre manuellement une scène spécifique. Un autre algorithme fournit à l'opérateur la possibilité de balayer une zone en utilisant une planification de trajectoire dans l'espace cartésien. Un troisième algorithme permet de planifier une trajectoire dans l'espace articulaire. Enfin, une adaptation de l'algorithme dans l'espace cartésien permet de poursuivre un point GPS. Ainsi, la caméra demeure orientée dans la direction du point GPS demandé malgré le déplacement de l'aéronef, et ce, selon les limites physiques du mécanisme. La cinématique inverse du système permet d'évaluer les positions articulaires requises pour orienter la caméra vers la coordonnée poursuivie.

Une fois le prototype terminé, il faudra l'optimiser pour respecter les limitations du véhicule quant au poids de la charge et à ses dimensions, et modifier son concept pour l'adapter à la caméra présentement à bord. Les algorithmes de contrôle resteront cependant les mêmes, ne nécessitant qu'un ajustement des variables du système.

Executive summary

The Autonomous Intelligent Systems Section, at Defence R&D Canada – Suffield, is developing an expertise in unmanned air vehicles (UAV), and is applying remote control airplanes with semi-autonomous control abilities to military applications. During trials held in September 2005 using the Silver Fox UAV, some deficiencies of the visual system were observed. Since the onboard camera is fixed, the operator has no control of the field of view. The vehicle operator needs to fly the aircraft back over the area of interest, in an orientation that places the suspicious area within the field of view of the camera. This task takes several minutes, depending on the winds. It was concluded that the Silver Fox needs an actuated camera that an operator can orient. That way, the flying operator wouldn't spend his time trying to fly over a scene repeatedly, hoping to give the camera operator a second chance to view the suspicious scene and identify threats that may be there. In addition, the ability to use the GPS location of the threat to control the orientation of the camera so that the threat is automatically kept in the field of view as the UAV maneuvers would be extremely useful.

In an attempt to address those observations, this report details a pan tilt camera mechanism that has been designed, modeled, built and controlled to provide the missing capabilities. The principle of a robotic arm has been studied to design the system. The resulting parallel robot consists of three revolute joints. A stepper motor rotates the camera vertically. A servomotor creates a pendulum movement of the upper part of the arm. A rod end acts as a passive joint, forcing the bottom part of the arm to rotate and pass by the pivot point of the rod end. The resulting motion of the camera is a spherical trajectory offering a 30° vertical angular motion of the field of view.

A MPC555 microcontroller controls the mechanism. Four different control algorithms are implemented and tested with the robotic camera. First, the system is controlled remotely using a linear analog joystick. The operator can track a specific scene manually while the airplane continues its path. Secondly, an algorithm provides the operator with the possibility to scan an area using joint-space trajectory planning, and another one using Cartesian-space trajectory planning. The operator gives joint coordinates or Cartesian coordinates for different points on the path which he wants the camera to follow. The algorithm interpolates a spline between each point to generate a smooth trajectory and then commands the actuators. Finally, an adaptation of the Cartesian-space algorithm leads to a GPS waypoint tracking control algorithm. It requests the GPS location in UTM coordinates of the robotic camera origin and of a waypoint to track. The system inverse kinematics gives the joint position required to orient the camera towards the waypoint. By looping continuously through the process, the camera keeps the scene in its field of view, within its physical limits.

The concept of using a robotic arm to orient the camera is interesting and offers flexibility for angular motion. When the prototype has been proven to be efficient for an aircraft application, the mechanism will need to be optimized to fit the payload limitations of the vehicle. It will also require design modification to adapt it to the camera currently used with the Silver Fox. However, the control algorithms will stay the same, requiring only an adjustment of the system variables.

Vincent, I., 2005. Articulated robotic camera design and control, for use in remote control of aircraft. DRDC Suffield TM 2005-253. Defence R&D Canada – Suffield.

Sommaire

La Section des Systèmes intelligents autonomes de R&D pour la défense Canada – Suffield développe actuellement une expertise dans le domaine des véhicules aériens sans pilote, en appliquant les technologies de télé-opération aux opérations militaires sur le terrain. Les essais conduits en septembre 2005, utilisant l'aéronef Silver Fox, ont révélé des déficiences au niveau du système de visualisation. La caméra de bord étant fixe, l'opérateur n'a aucun contrôle sur l'orientation du champ de vision de la caméra, et l'opérateur du véhicule doit ramener l'aéronef dans la zone à observer. Il a été conclu que le Silver Fox avait besoin d'une caméra actionnée que l'opérateur pourrait orienter. De cette manière, l'opérateur de vol ne survolerait pas répétitivement une scène, en espérant donner à l'opérateur de la caméra une seconde chance de visualiser la scène suspecte et d'identifier une menace possible. De plus, il serait extrêmement utile d'avoir la capacité d'utiliser la localisation GPS d'un site à observer pour contrôler l'orientation de la caméra et garder automatiquement le site dans le champ de vision durant les manoeuvres de l'aéronef.

D'après ces observations, un mécanisme de caméra panoramique et à inclinaison, ainsi que son contrôleur, ont été conçus, et un principe de bras robotisé a été étudié pour concevoir le système. Le robot parallèle résultant consiste en trois articulations à rotule. Un moteur pas à pas fait pivoter la caméra, qui regarde vers le bas, autour d'un axe verticalement. Un servomoteur crée un mouvement oscillatoire de la partie supérieure du bras. Un embout à rotule agit comme une articulation passive et force la partie inférieure du bras à pivoter et à passer par le point de pivotement de l'embout à rotule. Le mouvement de la caméra qui en résulte est une trajectoire sphérique couvrant un arc de 30˚.

Un microcontrôleur MPC555 contrôle le mouvement du mécanisme. Quatre algorithmes de contrôle sont élaborés et testés avec la caméra robotisée. Le système est d'abord contrôlé à distance à l'aide d'une manette analogue linéaire. L'opérateur peut suivre manuellement une scène spécifique pendant que l'aéronef continue son parcours. Un autre algorithme fournit à l'opérateur la possibilité de balayer une zone en utilisant une planification de trajectoire dans l'espace cartésien. Un troisième algorithme permet de planifier une trajectoire dans l'espace articulaire. L'opérateur fournit une séquence de coordonnées cartésiennes ou articulaires des points que la caméra doit suivre. Le contrôleur interpole une spline entre chaque point pour générer une trajectoire lisse, puis commande les actionneurs. Enfin, une adaptation de l'algorithme dans l'espace cartésien permet de poursuivre un point GPS. La caméra demeure orientée dans la direction du point GPS demandé malgré le déplacement de l'aéronef, et ce, selon les limites physiques du mécanisme. La cinématique inverse du système permet d'évaluer les positions articulaires requises pour orienter la camera.

Le concept d'un bras robotisé pour orienter la caméra est intéressant et offre une grande flexibilité dans le mouvement angulaire. Une fois le prototype terminé, il faudra l'optimiser pour respecter les limitations du véhicule quant au poids de la charge et à ses dimensions, et modifier son concept pour l'adapter à la caméra présentement à bord. Les algorithmes demeureront cependant les mêmes, ne nécessitant qu'un ajustement des variables du système.

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1. Introduction

The Autonomous Intelligent Systems Section (AISS), at Defence R&D Canada – Suffield, is developing an expertise in unmanned air vehicles (UAV), applying remote control airplanes with semi-autonomous control abilities to military field operation applications.

1.1 Context

In September 2005, AISS participated in trials involving military personnel to determine strategies for a field operation with the Silver Fox remote control airplane. A control station on the experimental proving ground at Suffield controlled the aerial vehicle on a threat recognition mission. Actors simulated threatening situations. Those sketches were unknown to the control station operators who had to fly over the area and detect, using the onboard video camera, the possible dangerous or suspicious situations. Figure 1 is a picture of the Silver Fox showing the camera payload.

Figure 1: Picture of the Silver Fox.

The video camera operators finding the threats noticed some imperfections in the visual system. Since the onboard camera is fixed, the operator has no control of the field of view on a scene that requires more visual attention. The vehicle operator needs to return the airplane to the area. This task can take several minutes, depending on the winds. When the camera operator sees something, he asks the flying operator the GPS position. As there is a time interval between the detection and the position reading, the chance to come back and see the same scene is decreased. Then, the operator draws a circuit around the waypoint taking the winds into account. The vehicle's semi-autonomous controller flies along the circuit. Unfortunately, the shape of the requested trajectory is rarely identical to the real trajectory since the airplane is confronted to the winds. Finally, the system allows the camera operator to zoom in and out. However, the resolution doesn't increase when zooming in. For these reasons, the performance of the camera operator was poor and the trials were unsuccessful.

After the trials, the team agreed the Silver Fox needed an actuated camera that the operator could orient. That way, the flying operator wouldn't spend his time trying to fly over a scene repeatedly, hoping to give the camera operator a second chance to view the suspicious scene and identify the threat.

1.2 Objectives

Attending a course at University of Calgary about robotic arms, I found interesting to apply this knowledge to design and build a camera motion control mechanism. Here are the leading objectives of the project.

1. Design a camera motion control system for generating a spherical range of motion.

2. The total vertical angular motion of the camera can be limited to 30°, since at an altitude of 300 feet it will provide the operator with a big enough field of view.

3. As the camera can see several square metres at a time, a very small movement of the camera involves an important displacement of the view area. For this reasons, the system actuators must provide a good angular resolution.

4. The operator must be able to remotely control (with a joystick for instance) the orientation of the camera to keep a scene that attracts its attention in the field of view.

5. When a GPS waypoint is obtained, the control system must keep the camera tracking this scene as long as it stays in the camera field of view.

6. The system should be able to scan an area autonomously.

7. This project studies if an articulated arm could be used to control a camera in a remote control airplane application.

The next sections cover the robotic camera design, its model, four different control algorithms applicable to a context of Silver Fox field operation, a discussion about the control of the mechanism and possible improvements.

This report is supported by a presentation that includes videos of the experiments.

2. Design

This section details the mechanism and its components.

2.1 System description

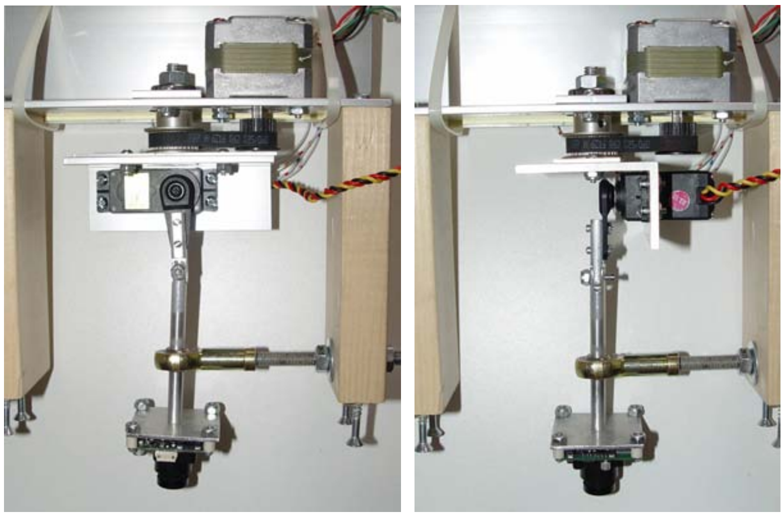

Figure 2: Face and side view of the camera mechanism.

The principle of a robotic arm is used to design a pan and tilt camera system. All trajectories lie on a spherical surface. Two revolute joints actuate the mechanism: a stepper motor rotates the camera about a vertical axis and a servomotor creates a pendulum movement of the upper part of the arm. A rod end creates a third revolute joint by forcing the second link of the arm to pass by a fixed point. Therefore, the use of a third actuator is avoided. See figure 1 for a picture of the mechanism.

Although the final design seems complex, the idea is simple. First, a timing belt pulley system transmits the stepper motor rotation to a vertical axis with a ratio 3:2. Thus, the resolution of the motor is increased from 1.8° to 1.35° per step. A nut installed at the upper end of the vertical axis maintains it into a radial bearing. The lower end of the axis holds the slave pulley of the timing belt pulley system. A plate is screwed into the pulley to hold the servo L-beam support. As the vertical axis must be aligned with the arm in vertical position, adjustment slots are machined into the plate and the L-beam. A servomotor is embedded into the L-beam. The arm consists of two links attached by a pin. The first link is fixed to the servo axis through a plate perpendicular to the axis. The second link supports the camera plate. Finally, the camera is bolted to the plate.

A micro-controller controls the system by modulating the pulse width signal sent to the servomotor and by setting the I/O pins high or low to command the stepper motor phases. A driver supplies the stepper motor with 6V. Section 2.3 details the electrical scheme of the driver. The micro-controller reads a joystick input using an analog-to-digital converter. Therefore, a remote control of the system is possible.

The micro-controller is programmed to control the robotic camera mechanism remotely and autonomously. Some control algorithms have been developed to study joint-space and Cartesian-space control of the system. Section 4 details those algorithms.

2.2 Components

MPC555

The camera micro-controller is a PowerPC based SS555 from Intec Automation Inc. (See figure 3) The 40 MHz MPC555 Motorola embedded microprocessor is a RISC PowerPC core with a floating-point unit. To realize the project, it has principally 8 pulse width modulation channels, 32 10-bit analog-to-digital converter pins, 8 general-purpose I/O pins, 2 time processor units with 16 independent channels each and 2 RS-232 serial communication interface ports. It supports the PowerPC interface cable (P&E ICDPPC In-Circuit Emulator/Debug cable).

Figure 3: SS555-DK development kit provided by Intec Automation Inc.

Servo

The project includes a high torque precision servomotor Hobbico HCAM0191 to actuate a revolute joint. This CS-70MG metal-geared super torque 2BB servo generates a 106.7 oz-in output torque. It requires 4.8V in the application and weighs 60 grams.

Stepper motor

A Japan Servo Co ltd. stepping motor, KP4M2-009, actuates the second revolute joint. Its resolution is 1.8° by step and it has 200 steps in full-stepping.

Camera

The project uses a black and white micro video camera supplied with 12V at 100ma. It provides a real time video signals that can be connected to a monitor and/or VCR. The camera consists of a CCD solid-state video sensor.

GPS

The last experiment presented in this report uses DGPS waypoints to orient the camera, as the aircraft camera payload would do to track a waypoint on the ground. For this specific application, a GPS Sokkia provides localization data. Its driver is programmed into the MIRO middleware architecture under Linux. An additional service sends the desired localization data by serial communication interface.

The GPS model is GSR2600. It uses the Real-Time Kinematic (RTK) technique that allows 1 to 2 centimetres position accuracy. The antenna providing differential GPS is a positioning data link (PDL) from Pacific Crest Corporation.

MIRO

MIRO is a distributed object oriented framework for mobile robot control, based on CORBA (Common Object Request Broker Architecture) technology. The MIRO core components have been developed in C++ for Linux, under the aid of ACE (Adaptive Communications Environment), an object oriented multi-platform framework for OS-independent inter-process, network and real time communication. They use TAO (The ACE ORB) as their ORB (Object Request Broker), a CORBA implementation designed for high performance and real time applications. [1]

2.3 Electrical scheme

This subsection details the electrical scheme of the stepper motor driver shown in figure 4. The micro-controller I/O outputs control the gate of the N-channel enhancement mode vertical DMOS FETs. When the gate gets a high signal, the 6V battery power supplies the stepper motor.

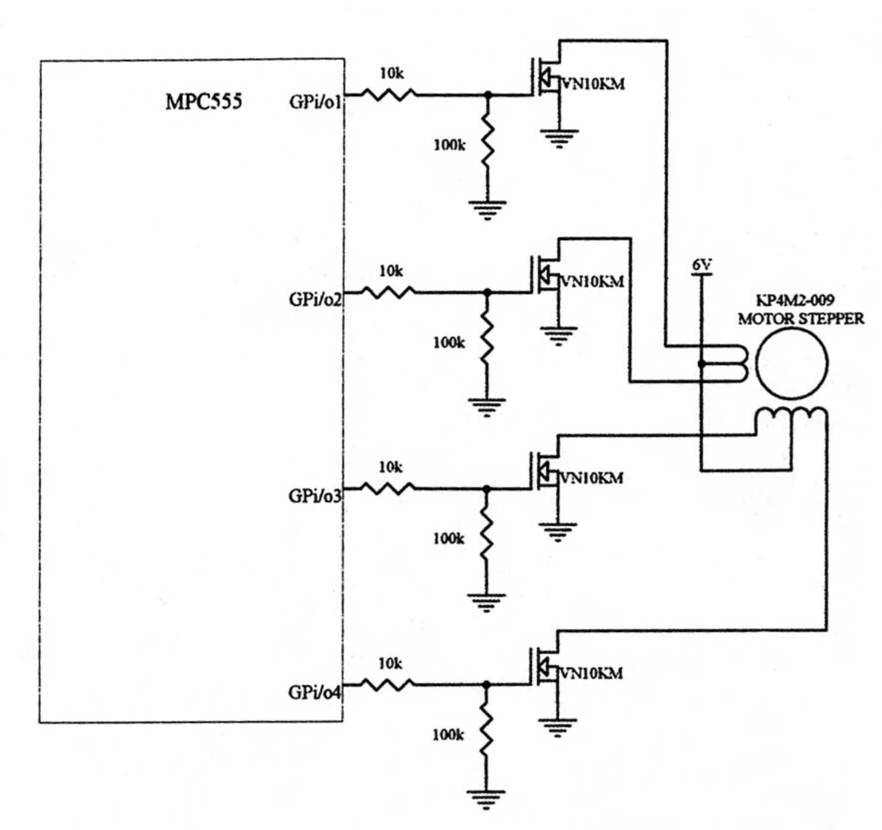

Figure 4: Electrical scheme of the stepper motor driver.

3. Model

The robotic camera mechanism consists of three revolute joints providing q_1, q_2 and q_3. Figure 5 shows the system frames. The first joint represents the vertical rotation produced by the stepper motor, the second joint is the angular motion of the first link produced by the servomotor and the third joint is the second link motion and it is created by the rod end. The rod end constraints the link to pass by a fixed point located at a distance h from the base frame along z_0. The link can slide in the rod end.

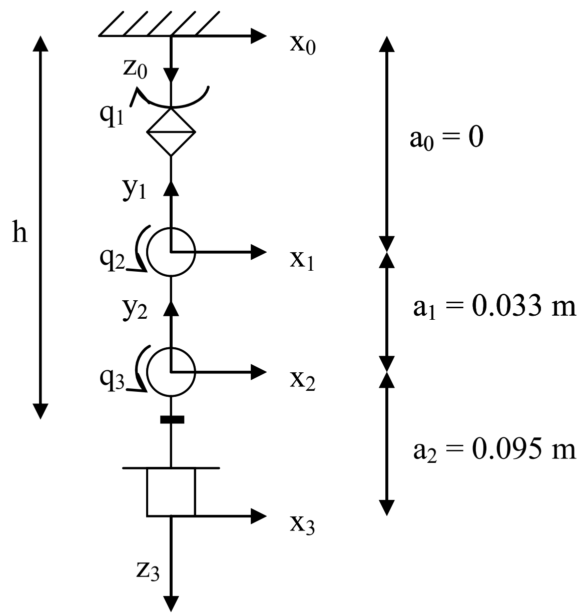

Figure 5: Robot frames representation.

3.1 Forward kinematics

The forward kinematics consists of the position matrix P of the n robot frames, and the homogeneous transformation matrices of the frames H_0^n.

$$P = \begin{bmatrix} 0 & a_1\cos(q_1)\sin(q_2) & -(a_2\sin(\psi) - a_1\sin(q_2))\cos(q_1) \\ 0 & a_1\sin(q_1)\sin(q_2) & -(a_2\sin(\psi) - a_1\sin(q_2))\sin(q_1) \\ 0 & a_1\cos(q_2) & a_2\cos(\psi) + a_1\cos(q_2) \\ 1 & 1 & 1 \end{bmatrix}$$

where $\psi = \text{atan2}(a_1\sin(q_2),(h-a_1\cos(q_2)))$.

Homogeneous transformation matrix of frame 1:

$$H_0^1 = \begin{bmatrix} \cos(q_1) & 0 & -\sin(q_1) & 0 \\ \sin(q_1) & 0 & \cos(q_1) & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Homogeneous transformation matrix of frame 2:

$$H_1^2 = \begin{bmatrix} \cos(q_2) & -\sin(q_2) & 0 & a_1 \sin(q_2) \\ \sin(q_2) & \cos(q_2) & 0 & -a_1 \cos(q_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$H_0^2 = H_0^1 H_1^2 = \begin{bmatrix} \cos(q_1)\cos(q_2) & -\cos(q_1)\sin(q_2) & -\sin(q_1) & a_1 \cos(q_1)\sin(q_2) \\ \sin(q_1)\cos(q_2) & -\sin(q_1)\sin(q_2) & \cos(q_1) & a_1 \sin(q_1)\sin(q_2) \\ -\sin(q_2) & -\cos(q_2) & 0 & a_1 \cos(q_2) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Some variables must be defined to express the frame 3 homogeneous transformation matrix. See figure 6 for the representation of the variables.

The variable x is the distance between the rod end and joint 3. The cosine law gives:

$$x = \sqrt{a_1{}^2 + h^2 - 2a_1 h \cos(q_2)}$$

Then θ is the interior angle between the links a_1 and a_2. The sine law gives:

$$\theta = \pi - a\sin\left(\frac{h\sin(q_2)}{x}\right)$$

Finally, q_3 can be calculated with the following equation.

$$q_3 = \theta - \pi$$

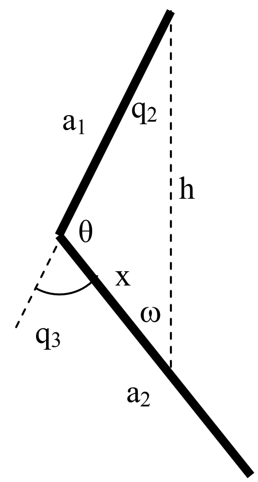

Figure 6: Representation of joint 2 and 3 with corresponding variables.

The sign of q_3 has been changed to respect the frame orientation. Then, it is possible to evaluate the homogeneous transformation matrix of frame 3:

$$H_2^3 = \begin{bmatrix} \cos(q_3) & 0 & \sin(q_3) & a_2\sin(q_3) \\ \sin(q_3) & 0 & -\cos(q_3) & -a_2\cos(q_3) \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$H_0^3 = H_0^2 H_2^3$$

$$H_0^3 = \begin{bmatrix} \cos(q_1)\cos(q_2+q_3) & -\sin(q_1) & \cos(q_1)\sin(q_2+q_3) & a_2\cos(q_1)\sin(q_2+q_3)+a_1\cos(q_1)\sin(q_2) \\ \sin(q_1)\cos(q_2+q_3) & \cos(q_1) & \sin(q_1)\sin(q_2+q_3) & a_2\sin(q_1)\sin(q_2+q_3)+a_1\sin(q_1)\sin(q_2) \\ -\sin(q_2+q_3) & 0 & \cos(q_2+q_3) & a_2\cos(q_2+q_3)+a_1\cos(q_2) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

4. System control and applications

This section presents four different types of control tested with the robotic camera: remote control, joint-space trajectory planning, Cartesian-space trajectory planning and finally a variation of this last one, a GPS waypoint tracking control algorithm.

4.1 Remote control

A remote control algorithm is implemented to allow an operator to orient the camera manually. Thus, the person can track a specific scene manually while the airplane continues its path.

An analogical joystick with two linear axes is used to control the mechanism. One analog signal is converted into a pulse width modulated signal that is linear with respect to the analog input to command the servomotor.

The following equation expresses the servo pulse width.

$$\text{Pulse width} = 1625 + (\text{analog input} - 550) * F$$

In this equation, 1625 is the middle position of the servo (i.e. the vertical position of the camera) and 550 is the joystick centre position analog signal. F is a multiplicative factor to cover the entire range of the servo. The servo ranges from 750 to 2500 ticks for a 20ms period, which means about 190°. With F equals 1.5, the range is 1075 to 2450 and it covers 180°. This is sufficient for the system since the servo won't cover all that range.

The pulse width value is compared to the limit constraints before the signal is sent to the servo. Those limits are established to avoid collision between the camera and the rod end. There is a maximum and a minimum limit to take into account the "elbow in" and "elbow out" solutions, or the 0° and the 180° positions of the stepper motor relatively to the rod end. The duty cycle varies between 6.58% and 9.78% for a 20ms period signal.

In the case of the stepper motor, an analog signal over 700 indicates a counter clockwise stepping and below 400 a clockwise stepping. In between those two values, no stepping occurs.

The stepper motor is employed in full-step mode. Using the I/O pins of the micro-controller, the four phases are activated alternatively. For a clockwise stepping, the phase order is 1-2-3-4, and in counter clockwise stepping 4-3-2-1. Between each phase, the motor requires a short delay that is set to 0.035 second for a smooth progression of the mechanism.

4.2 Joint-space control

In joint-space trajectory planning, the robotic mechanism is controlled with joint coordinates. This provides a smooth progression of the joints and it is simple to compute.

Two joint positions are provided to the algorithm: the current and the requested position of the joints q_{cur} and q_{req}. A spline Q is then generated for P points between q_{cur} and q_{req}.

$$q_{cur} = \begin{bmatrix} q_{1\_cur} \\ q_{2\_cur} \end{bmatrix}, \quad q_{req} = \begin{bmatrix} q_{1\_req} \\ q_{2\_req} \end{bmatrix}, \quad Q_i = \begin{bmatrix} q_{1\_i} \\ q_{2\_i} \end{bmatrix}$$

For every point i between q_{cur} and q_{req}, the joint positions Q_i are evaluated with:

$$Q_i = q_{cur} + i * (q_{req} - q_{cur}) / P$$

The stepper motor is commanded by $Q_i(1)$. This angle is compared to the current angle of the motor to get the number of steps required to reach the requested position.

$$\text{Number of steps required} = Q_i(1) / \text{Resolution} - \text{actual step count}$$

$$\text{Resolution} = 360° / (\text{motor number of steps} * \text{pulley ratio})$$

As the system is designed with a 200-step motor and a 3:2 timing belt pulley ratio, the resolution is 266.7 steps per revolution or 1.35°. The 'number of steps required' equation is valid for a system designed to execute only one revolution. This avoids wires wrapping around the mechanism and damage the equipment.

The stepper motor is employed in full-step mode. Using the I/O pins of the micro-controller, the four phases are activated alternatively. For a positive number of steps required, the stepping is counter clockwise; if negative, the stepping is clockwise. Between each phase, the motor requires a short delay that is set to 0.035 second for a smooth progression of the mechanism.

The servo is commanded by sending a linear conversion of $Q_i(2)$ into a pulse width modulation value.

$$\text{Pulse width} = m * Q_i(2) + 1625$$

$$m = (2450 - 800) / (90° + 90°) = 9.17$$

where m is the servo linear slope constant of the pulse width versus the angle and 1625 is the center position pulse width value.

Joint-space trajectory planning is simple to implement. The following experimentation aims to control the system in joint coordinates. To test it, a simple pattern is executed using a set of joint coordinates. The context of this test is to act as a surveillance camera in a room. The idea is to optimize the field of view of the camera without wrapping itself in the electric wires. Figure 7 represents the resulting trajectory experimented. The camera follows this pattern executing continuously an 8-shape loop. Thus, $Q_i(1)$ stays between 0° and 360° and the electrical wires are not wrapped around the mechanism. To proceed, the following joint coordinates are passed continuously to the algorithm: (0°, 33°), (45°, 33°), (135°, 33°), (180°, 33°), (180°, -33°), (135°, -33°), (45°, -33°). The servo allows a maximum angle of 33° to avoid collision of the camera with the rod end. Between those points, a spline is obtained by interpolating 20 points between each coordinate. The result is a smooth progression of the camera describing the pattern.

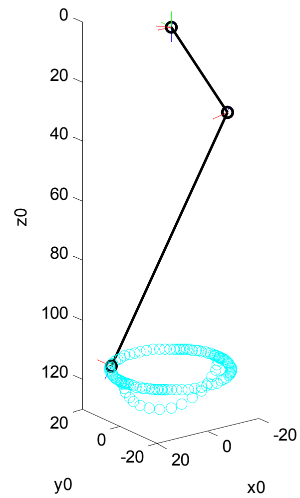

Figure 7: Joint-space pattern.

4.3 Cartesian space control

In this mode of control, the algorithm converts Cartesian coordinates into joint positions. Unlike the joint-space trajectory planning, it creates a spline in Cartesian coordinates to provide a linear displacement of the end effector, and then converts the result into joint angles. The algorithm requires the Cartesian coordinate of a waypoint to orient the camera in this direction. The implementation of this algorithm is a lot more complex than the forward kinematics used in joint-space control. Figure 8 represents the geometry of the system and the variables used in the following mathematics.

The next equation gives the relative coordinate position ΔP of a waypoint P to the origin P_0 of the mechanism. The origin is established at the base of the robotic arm. It is the junction of the stepper motor axis and the servo axis.

$$\Delta P(\Delta x, \Delta y, \Delta z) = P(x,y,z) - P_0(x_0,y_0,z_0)$$

A spline S is generated for N points between the requested relative waypoint coordinate ΔP_2 and the current relative waypoint coordinates ΔP_1. For every point between ΔP_1 and ΔP_2, the positions are evaluated:

$$S_i(x,y,z) = \Delta P_1(x,y,z) + i\left(\frac{\Delta P_2(x,y,z) - \Delta P_1(x,y,z)}{N}\right)$$

where i represents the number of incremented points in the spline. (i equals 0 to N) The rest of this section is applied to each iteration $S_i(x,y,z)$ of the spline.

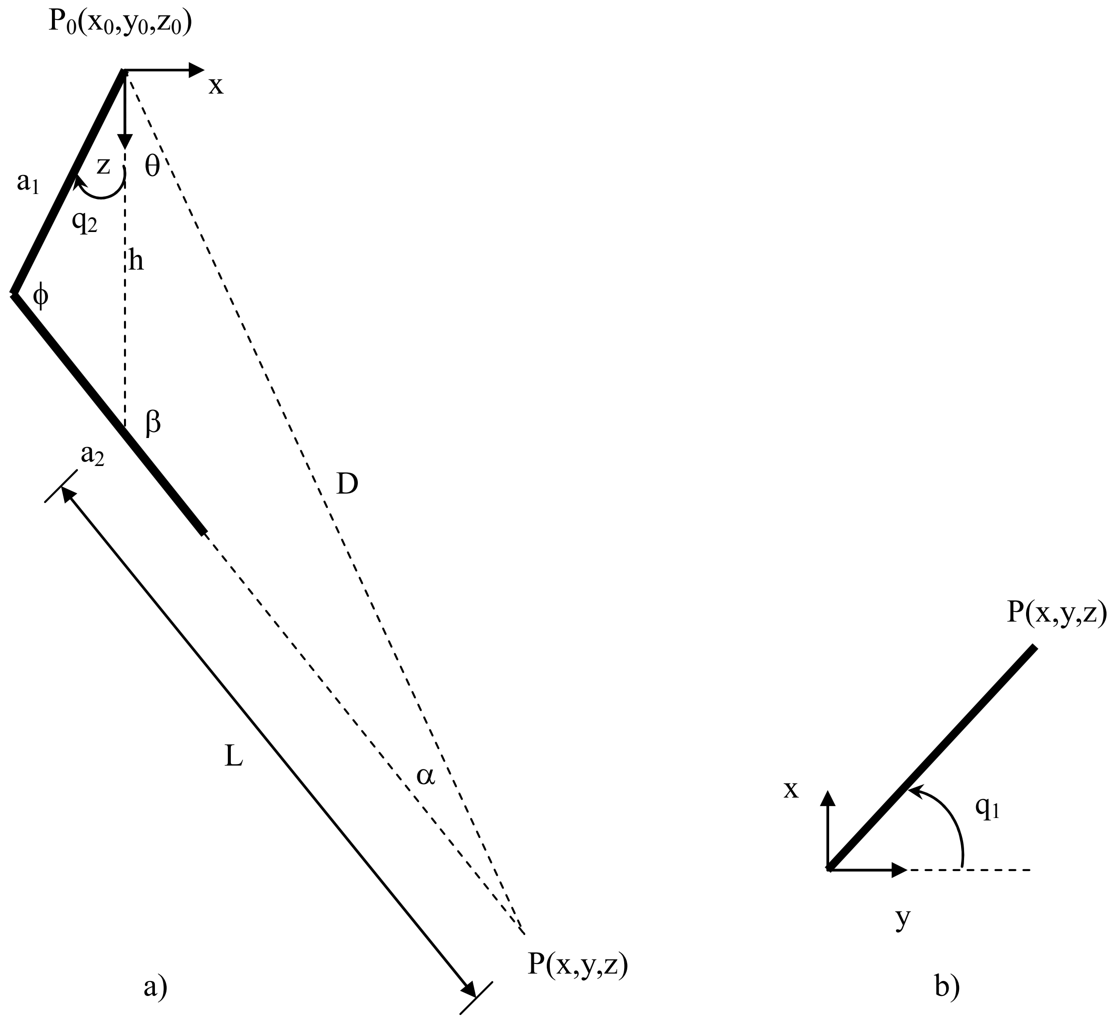

Figure 8: Geometry of the system with corresponding variables: a) x-z view and b) x-y view.

First, a required stepper motor orientation angle q_1 is obtained to orient the system in the waypoint direction for the x-y plane.

$$q_1 = \text{atan2}(S_i(x), S_i(y))$$

This angle is in the range of $-\pi$ to π. For a practical purpose, it is converted into degrees and then in a positive angle between 0° and 360°. If the absolute value of the current joint position is more than 90° from the requested q_1, the system opts for the shorter rotation and reverses the elbow solution.

To find the servo joint position q_2, it is useful to calculate the distance D between the waypoint and the system origin and the angle θ from D to the base frame z axis.

$$D = \sqrt{S_i(x)^2 + S_i(y)^2 + S_i(z)^2}$$

$$\theta = \begin{cases} 0 & if\ S_i(x,y) = (0,0) \\ a\sin\left(\dfrac{\sqrt{S_i(x)^2 + S_i(y)^2}}{D}\right) & otherwise \end{cases}$$

Now is evaluated the distance L between the rod end and the waypoint using the cosine law. In the equation, h represents the distance between the system origin and the rod end.

$$L = \sqrt{D^2 + h^2 - 2dh\cos(\theta)}$$

The angle between D and L is α. The cosine law gives:

$$\alpha = a\cos\left(\frac{h^2 - D^2 - L^2}{-2DL}\right)$$

To evaluate a required q_2 to orient the system in the waypoint direction, two other angles need to be calculated: β and ϕ.

$$\beta = \pi - \theta - \alpha$$

$$\phi = \pi - a\sin\left(\frac{h\sin(\pi - \beta)}{a_1}\right)$$

$$q_2 = \beta - \phi \text{ (except in reverse elbow solution where } q_2 = \phi - \beta\text{)}$$

The joint position q_2 is then converted into degrees.

The servo is commanded by sending a linear conversion of q_2 into a pulse width modulation value.

$$\text{Pulse width} = m * q_2 + 1625$$

$$m = (2450 - 800) / (90° + 90°) = 9.17$$

where m is the servo linear slope constant of the pulse width versus the angle and 1625 is the centre position pulse width value.

The stepper motor is commanded by q_1. This angle is compared to the current angle of the motor to get the number of steps required to reach the requested position.

$$\text{Number of steps required} = q_1 / \text{Resolution} - \text{actual step count}$$

$$\text{Resolution} = 360° / (\text{motor number of steps} * \text{pulley ratio})$$

To test the Cartesian-space trajectory planning algorithm, a C-shape is executed. Figure 9 shows the pattern. The position coordinates of the ends of each segment are provided to the algorithm. A spline of 20 interpolated points is created to trace the straight lines. The result validates the correctness of the algorithm since the pattern is properly executed. As it is difficult to make this conclusion by looking at the camera motion, a laser pointer is substituted to the camera as shown in figure 10. The red light traces the segments on the black board, demonstrating that the inverse kinematics is modeled adequately.

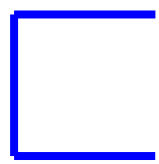

Figure 9: C-shape pattern for the Cartesian-space trajectory planning.

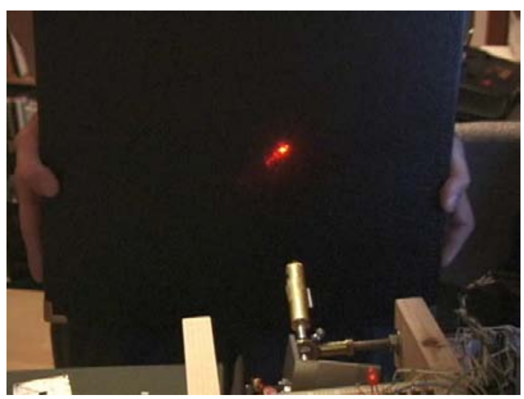

Figure 10: A laser pointer is substituted to the camera to validate the Cartesian-space trajectory planning algorithm.

4.4 DGPS waypoint tracking

The last control algorithm implemented with the robotic camera is for DGPS waypoint tracking. The context is when the remote control aircraft is flying over an interesting area, the control station operator set on is computer map the DGPS waypoint. Then, the camera tracks this waypoint by keeping the lens oriented in this direction. Thus, the camera operator can continue to look at the area even if the vehicle is flying away. It gives more time to investigate the scene.

The algorithm is a modification of the inverse kinematics implemented in section 4.3.

First, the micro-controller needs the position of the aircraft and the waypoint of the computer map. As the vehicle has an altitude of 300 feet and more, no coordinate system transformation is required to convert the GPS location from the onboard GPS coordinate system to the camera origin. It is negligible. For the experiment, the DGPS driver is implemented on a laptop using Linux as operating system and MIRO as the multiprocessor architecture. The GPS process sends events to a communication process every time it gets a new data package. The communication process sends UTM easting, UTM northing and altitude by serial communication interface. The micro-controller reads those three data and then proceeds to the inverse kinematics calculations. It had been decided to work that way since time was missing to write a GPS driver for the micro-controller, and it was already done under MIRO.

For the experiment, the camera localization is previously measured and doesn't change. Only the tracked DGPS system moves. See figure 11 for the experiment setting.

Figure 11: GPS experiment setting. The DGPS system is moved on the ground and the camera system tracks it from a high platform. It was noticed that no satellite was seen when the system was between the two trucks so the trucks were replaced by ladders.

The first calculation determines the coordinate difference ΔP between the tracked waypoint P and the base frame origin of the camera P_0.

$$\Delta P(\text{altitude}) = P(\text{altitude}) - P_0(\text{altitude})$$

$$\Delta P(\text{easting}) = P_0(\text{easting}) - P(\text{easting})$$

$$\Delta P(\text{northing}) = P(\text{northing}) - P_0(\text{northing})$$

The Universal Transverse Mercator (UTM) coordinate system provides northing from the equator and easting from the central meridian in meters. The differentiation expresses the result in the quadrants around the camera origin.

The first angle to evaluate is the stepper motor orientation q_1. It is the angle between the camera East axis (y_0) and the waypoint localization. The angle is positive if measured counter clockwise. See figure 12 for the schema with the variables.

$$q_1 = \text{atan2}(\Delta P(\text{easting}), \Delta P(\text{northing}))$$

The result is converted into degrees. For simplicity, the angle is kept between 0° and 360°. If negative, 360° is added to q_1 to get a positive angle.

To find the servo joint position q_2, it is useful to calculate the distance D between the waypoint and the system origin, and the angle θ from D to the base frame z_0 axis.

$$D = \sqrt{\Delta P(\text{altitude})^2 + \Delta P(\text{easting})^2 + \Delta P(\text{northing})^2}$$

$$\theta = \begin{cases} 0 & \textit{if } \Delta P(\text{easting}, \text{northing}) = (0,0) \\ a\sin\left(\dfrac{\sqrt{\Delta P(\text{easting})^2 + \Delta P(\text{northing})^2}}{D}\right) & \textit{otherwise} \end{cases}$$

Now is evaluated the distance L between the rod end and the waypoint using the cosine law. In the equation, h represents the distance between the system origin and the rod end.

$$L = \sqrt{D^2 + h^2 - 2Dh\cos(\theta)}$$

The angle between D and L is α. The cosine law gives:

$$\alpha = a\cos\left(\frac{h^2 - D^2 - L^2}{-2DL}\right)$$

The angle between L and h is β. It is evaluated with the next equation.

$$\beta = \pi - \theta - \alpha$$

The interior angle ϕ from link 1 to link 2 is expressed with:

$$\phi = \pi - a\sin\left(\frac{h\sin(\pi - \beta)}{a_1}\right)$$

Finally, the servomotor angle q_2 is the difference between β and ϕ. The joint position is then converted into degrees.

The servo is commanded by sending a linear conversion of q_2 into a pulse width modulation value.

$$\text{Pulse width} = m * q_2 + 1625$$

$$m = -(2450 - 800) / (90° + 90°) = 9.17$$

where m is the servo linear slope constant of the pulse width versus the angle and 1625 is the centre position pulse width value.

The stepper motor is commanded by q_1. This angle is compared to the current angle of the motor to get the number of steps required to reach the requested position.

$$\text{Number of steps required} = q_1 / \text{Resolution} – \text{actual step count}$$

$$\text{Resolution} = 360° / (\text{motor number of steps} * \text{pulley ratio})$$

Since the weather was very cold the week of the experimentation, the computers were not working properly and unfortunately the system could not be tested outdoor. An alternative was to use a log file of GPS waypoint instead. A log file had been prepared previously when a vehicle was driven on the experimental proving ground in Suffield. Thus, the control algorithm could be tested by simulation.

To proceed, the camera localization was fixed by triangulation to keep the whole path in the centre of the camera field of view. An altitude of 300 feet was appropriate. Using the laser pointer instead of the camera, the path executed by the mechanism was seen on a board and traced to then compare it to the real path. By triangulation again, it was verified that the resulting pattern was properly sized. The result confirmed the correctness of the algorithm.

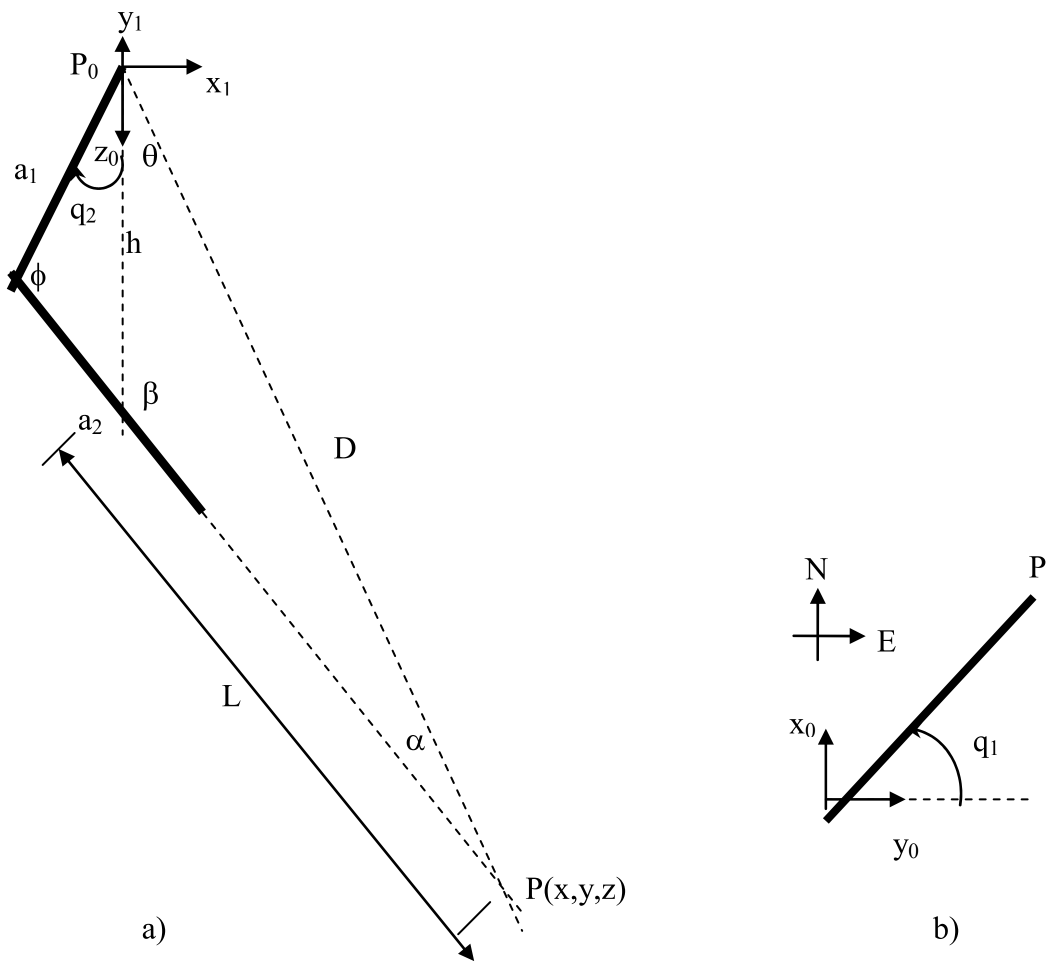

Figure 12: Geometry of the system with corresponding variables for the DGPS waypoint tracking algorithm: a) x-z view and b) x-y view.

5. Discussion and improvements

The remote control algorithm was easy to implement and very useful to verify if the mechanism was working properly. The first remote attempts demonstrated that the addition of a revolute joint to keep the camera lens always in the same orientation would improve the video view. With the actual design, the image rotates continuously and the operator looses spatial orientation.

In joint-space control, the algorithm was simple to implement and provided a smooth progression of the camera. The advantage to control that way is that it is computationally inexpensive. However, it is difficult for the operator to evaluate the joint positions required to look in a specific location. The Cartesian-space control allows the operator to give a location for the camera to look at. It is more instinctive, but computationally expensive since it has to evaluate the inverse kinematics of the system.

To complete the waypoint tracking algorithm, it will have to take into account pitch, roll and yaw of the aircraft. They influence the orientation of the camera. The Cartesian North and East wouldn't correspond to the camera's idea of North and East without integrating gyro angles to the algorithm. Although the driver for the 3DM-G MicroStrain gyro enhanced orientation sensor was prepared, and the data serially transmitted to the MPC555, there was no time to include gyroscope data into the implementation.

Another improvement to the system would be to include a feedback for the stepper motor rotation. The present design doesn't have feedback. When steps are skipped the micro-controller can't rectify the situation and it looses the predefined origin. Use of a servomotor could solve the feedback problem. However, it rotates on 180° only. A combination of pulleys with a ratio of 2:1 would increase the rotation range to 360°.

When the prototype will be proven efficient for an aircraft application, the mechanism will need optimization to fit the payload limitations of the vehicle. It will also need design modification to adapt it to the camera currently used with the Silver Fox.

The concept of robotic arm to orient the camera is interesting and offer design flexibility to get a wider or narrower angular motion range. A spherical bearing acting as a camera pivot reduces the number of motors required to actuate the mechanism.

6. Conclusion

This project aimed to design, model and control a camera moving mechanism based on an articulated arm. All the project objectives have been met. First, a camera moving mechanism allowing a spherical trajectory was designed. Its total vertical angle movement is limited to 30° as requested. The system actuators provide a good angular resolution, 1.35° for the stepper motor and 0.1° for the servomotor. The operator can control the camera remotely with a joystick to keep a scene that attracts its attention in the field of view up to the limits of the system. With the joint-space and the Cartesian-space control algorithms, the system showed the possibility to scan an area autonomously. Finally, when GPS waypoints are provided, the control system keeps the camera tracking the scene as long as it stays in the system limits.

This project is a first step to solve the Silver Fox camera problem. The concept of robotic arm to orient the camera is interesting and offers flexibility for angular motion. When the prototype will be ready for an aircraft application, the mechanism will need optimization to fit the payload limitations of the vehicle. It will also need design modification to adapt it to the camera currently used with the Silver Fox. However, the control algorithms should stay the same with adjustment of the variable values.

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The Autonomous Intelligent Systems Section, at Defence R&D Canada – Suffield, is developing expertise in unmanned air vehicles (UAV), and is applying remote control technologies to military applications. During trials held in September 2005, using the Silver Fox UAV, some deficiencies of the visual system were observed, and it was concluded that the Silver Fox needs an actuated camera that an operator can orient to investigate suspicious scenes and identify threats. In addition, the ability to use the GPS location of the threat to control the orientation of the camera so that the threat is automatically kept in the field of view as the UAV maneuvers would be extremely useful.

Based on those observations, a pan tilt camera mechanism is designed, modeled, built and controlled. The principle of a robotic arm is studied to design the system. The resulting parallel robot consists of three revolute joints providing motion through a 30˚ vertical arc.

Four different control algorithms were implemented and tested with the robotic camera. First, the system is controlled remotely by an operator to track a specific scene manually. Two other algorithms provide the operator with the possibility to scan an area using joint-space or Cartesian-space trajectory planning. Finally, an adaptation of the Cartesian-space algorithm leads to a GPS waypoint tracking control algorithm. The system inverse kinematics gives the joint position required to orient the camera with the waypoint. By looping continuously through the process, the camera keeps the scene in its field of view with respect to its physical limits.

When the prototype is ready for an aircraft application, the mechanism will need to be optimized to fit the payload limitations of the vehicle and will required design modifications to adapt it to the onboard camera. However, the control algorithms will stay the same, requiring only an adjustment of the system variables.

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