Obstacle Avoidance Algorithm using Gradient Based Swarm Techniques

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***Abstract*—In this paper, a hybrid approach to obstacle avoidance, based on Particle Swarm Optimisation is proposed. This method provides significantly faster convergence, compared to classical approaches using potential fields and gradient descent. The potential functions being used are presented, along with the results, one would obtain by employing gradient descent, for comparison. The results obtained by using hybrid-algorithm, clearly show the significant reduction in number of iterations taken for convergence, in comparison to the exponential time, typically taken by gradient descent.**
The penultimate section explains the approach taken to adapt the algorithm being proposed, for applications with GPS coordinates. Experimental results for the same are also presented herewith.

Keywords*—*Obstacle Avoidance; Particle Swarm; Potential Field

I. Introduction

The applications of obstacle avoidance, are significant in many fields like robotics, video-game A.I., or general purpose navigation. This paper provides an approach to solve the problem of moving a point-object from a starting point to a target destination point, by avoiding obstacles present on the way, by making use of potential fields and a gradient-based particle swarm optimisation method. The work of Latombe [1], acts as a foundation to this paper. The work of Khatib [2] first mentions the concept of potential fields, for path-planning. This approach sought to generate paths by descending a point along its gradient, through the search-space, by subjecting it to attractive and repulsive potential forces. Many new methods employing virtual potential fields where proposed, which aimed to improve upon the various shortcomings of the potential field approach [3]. The vast multitude of path planning algorithms, which make use of potential fields, often use variations of Gradient Descent.
Particle Swarm Optimisation(PSO) [4] was developed by Eberhart and Kennedy, as a computational-evolutionary algorithm. It draws inspiration from the social behaviour of bird flocks, and fish schools, to optimise the objective function. Potential solutions to the optimization problem-represented as particles -update their position and velocity within the search space, by taking its own best experience, and the best experience of the swarm as a whole. This paper presents a novel approach to solving the problem of obstacle avoidance, which exhibits faster convergence, compared to conventional methods employing gradient descent, by using a hybrid method incorporating features of both PSO and Gradient Descent [5]. Section II elucidates the concept of Potential Fields, and their design in this paper. Section III presents the hybrid algorithm being proposed, along with a flowchart explaining the same. Section IV verifies the hypothesis being presented, and provides simulation results, that compare the efficiency and speed of convergence between conventional potential field and the improved hybrid algorithm being presented. Section V deals with the GPS implementation, and also provides generated results and experimental results using an actual UAV. Section VI gives the conclusion to this paper, and also mentions future works.

II. Artificial Potential Functions

This section deals with the design of the artificial potential field functions being used in this paper. It also introduces the potential fields, used to navigate paths to the target. This paper shall restrict its discussion to two-dimensions, for the sake of simplicity. The start and destination points shall be represented by $\mathbf{p}_s=[\mathbf{x}_1^s, \mathbf{x}_2^s]$ and $\mathbf{p}_d=[\mathbf{x}_1^t, \mathbf{x}_2^t]$, where the superscripts represent the dimension. Obstacles may also be defined in a similar manner; this paper shall limit the type of obstacles being discussed to circles, and shall only consider static obstacles in its scope. The centre points of circular obstacles are represented as $\mathbf{p}_{obs}=[\mathbf{x}_1^{obs}, \mathbf{x}_2^{obs}]$ in this paper, with radius $\mathbf{r}_{obs}$.
Following conventional definitions in prior literature, the potential function is defined as the sum of the total attractive, and repulsive potential acting on the point-object by the destination point and obstacle centres respectively. Concretely, this is given by:

$$U(\mathbf{p}) = U_{att}(\mathbf{p}) + Urep(\mathbf{p}) \tag{1}$$

The attractive and repulsive potentials are defined as:

$$U_{att}(\mathbf{p}) = \frac{1}{2}\xi\|\mathbf{p}-\mathbf{p}_d\|^2 \tag{2}$$

$$U_{rep}(\mathbf{p}) = \frac{1}{2}\eta\frac{1}{1+\left(\frac{\|\mathbf{p}-\mathbf{p}_{obs}\|}{\mathbf{r}_{obs}}\right)^{2n}} \tag{3}$$

ξ is a positive scaling factor, p is the position vector of the robot, $\mathbf{p}_d$ is the position vector of the destination, and η is another positive scaling factor.
The attractive potential is defined conventionally, as the squared-distance to the target. The repulsive potential function

is defined with respect to the Butter- worth frequency response of the n-th order. The function was chosen due to its maximal-flatness property [6], which prevents the repulsive field from interfering too much with the global minimum of the potential field, as it drops rapidly outside of the region of obstruction, and rises strongly within it.

From the above definitions, the artificial force which drives the point-object is given by the gradient of the potential function. However, it should be noted that it is often only necessary, to resort to numerical gradient methods, as simple as the central difference operator. Thus,

$$V(\mathbf{p}) = \nabla U(\mathbf{p}) \tag{4}$$

In actuality, the artificial force as defined above is the velocity of the point-object.

Therefore, one can make use of the iterative gradient-descent algorithm[7] , or any numerical Ordinary Differential Equation solver, to find the path to the destination:

$$\mathbf{x}_{n+1} = \mathbf{x}_n - \lambda \nabla f(\mathbf{x}_n) \tag{5}$$

Where, λ is often referred to as the learning rate in machine learning.

III. Obstacle Avoidance Algorithm

A. Particle Swarm Optimisation

The PSO algorithm proposed by Kennedy and Eberhart [4] attempts to simulate the behaviour of fish schools and bird flocks. The algorithm uses a heuristic approach to optimisation problems, by making use of a swarm of potential solutions within a search-space called particles. Optimal solutions are found using the local history of the performance of each particle, along with the global best position achieved, in an iteration.

Considering a swarm of N particles, with Velocities $\mathbf{V}_n^k$ and $\mathbf{X}_n^k$ at iteration k (such that, n ϵ[1,N]), where the number of dimensions of each these vectors, equals the number of dimensions of the search-space; The updated position of each particle in the swarm is calculated as:

$$\mathbf{V}_n^{k+1} = \omega \mathbf{V}_n^k + c_1 r_1 (\mathbf{p}Best_n - \mathbf{X}_n^k) + c_2 r_2 (\mathbf{g}Best_n - \mathbf{X}_n^k) n \tag{6}$$

$$\mathbf{X}_n^{k+1} = \mathbf{X}_n^k + \mathbf{V}_n^{k+1} \tag{7}$$

Where, c_1 is the social factor, which pulls the particle towards its local best solution, **p**Best; c_2 is the global factor, which pulls the particle towards the best solution achieved so far, **g**Best. The inertia W is used to control the extent to which the previous history of velocities, contribute to the current velocity. A large value of inertia, encourages exploration of the search-space, whereas smaller values promote local exploration. Therefore, it is important to reduce the value of inertia, to allow convergence at the destination. In this paper, the variation is done by using:

$$\omega = \omega e^{-\frac{\|\mathbf{g}Best - \mathbf{p}_d\|}{\mathbf{d}_0}} \tag{8}$$

ω_0 is the initial inertia, preferably greater than 1 to enable global search initially.d 0 is the critical distance below which the inertia drops below 63%. However, to simulate a real-time system, it is important to have a measure of elapsed time ,or time-intervals between iterations. By making the following modifications, PSO can be made dynamic, by multiplying interval-step values to the velocities when updating positions, this allows PSO to be used in real-time obstacle-avoidance systems:

$$\mathbf{V}_n^{k+1} = \omega \mathbf{V}_n^k + \frac{c_1}{\Delta t} r_1 (\mathbf{p}Best_n - \mathbf{X}_n^k) + \frac{c_2}{\Delta t} r_2 (\mathbf{g}Best_n - \mathbf{X}_n^k) \tag{9}$$

$$\mathbf{X}_n^{k+1} = \mathbf{X}_n^k + \mathbf{V}_n^{k+1} \Delta t \tag{10}$$

B. Hybrid Algorithm

The modifications made to PSO in the previous subsection, provides a new intuition of looking at the obstacle avoidance problem. Instead of using a single particle, that employs gradient descent for obstacle avoidance, using potential fields, this section illuminates the novel approach of using a swarm of particles, for obstacle avoidance. Much as how an actual flock of birds would fly to a common destination, the combination of PSO and gradient descent gives interesting results.

Instead of merely descending along a gradient, and avoiding obstacles by virtue of their interaction via repulsive potential fields, one can further improve upon the results by simultaneously employing PSO, [5] to optimise the distance to the destination. The block diagram, as shown in fig.1 briefly highlights the overall functionality of the proposed algorithm. By accumulating the various Global-Best positions over many iterations, a path between the starting-point and destination can be found.

By clamping the maximum velocities of particles in the swarm, the passing through of obstacles due to very large velocities and finite time-steps can be avoided. Indeed, this is a common problem in discrete-time simulations of physical and kinematic phenomena. The concept of the time-step mentioned here, is essentially abstract, acting as a value representing the degree of discretisation, rather than of temporal variations. Interesting results are obtained, when the velocity of the Global-Best Position is clamped differently than its neighbouring particles. When the maximum velocity of the global best position is lesser than that of its neighbours, the neighbouring particles are encouraged to act as a "cloud-of-avoidance", encouraging them to search locally for obstacles.

The updated position and velocity are as follows:

$$\mathbf{V}_n^{k+1} = \omega \mathbf{V}_n^k + \frac{c_1}{\Delta t} r_1 (\mathbf{p}Best_n - \mathbf{X}_n^k) + \frac{c_2}{\Delta t} r_2 (\mathbf{g}Best_n - \mathbf{X}_n^k) - \frac{\lambda}{\Delta t} \nabla (f(\mathbf{X}_n))$$

$$\mathbf{X}_n^{k+1} = \mathbf{X}_n^k + \mathbf{V}_n^{k+1} \Delta t \tag{11}$$

The Hybrid PSO-Gradient Algorithm being proposed is as given in algorithm-1.

The last term in the velocity expression, as shown in algorithm 1, is the weighted gradient at the point $\mathbf{X}_n$, which is the same as the gradient term found in equation (5). The velocity update presented above, is an adaptation of the GPSO algorithm [5].

Thus, the hybrid algorithm being proposed is the weighted sum of the PSO and gradient descent algorithms.

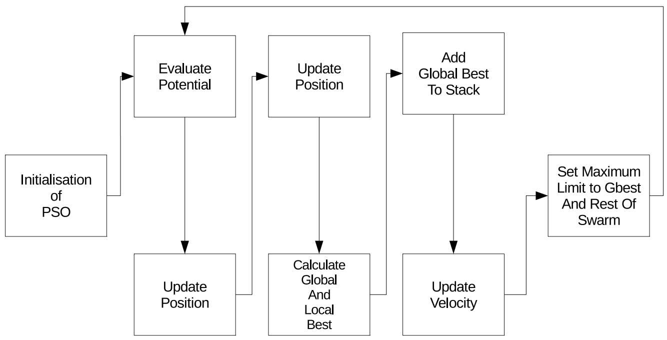


Fig. 1. Block diagram of algorithm

Algorithm 1 Hybrid PSO-Gradient Descent

1: Initialise a swarm of random particles around the starting point.
2: Initialise the velocities of all particles to be zero.
3: Evaluate the Potential value of each swarm particle.
4: Iterate over the particles and find the local best positions of each particle, and the global best
5: Update inertia as mentioned earlier in equation (8).
6: To simulate the behaviour of real-world objects and to prevent passing through obstacles due to very large velocities, set upper limits to the magnitude of the swarm velocities, as:
7: **if** $\|\mathbf{V}_{gBest}\| \geq \mathbf{V}_{maxGBest}$ **then**
8: $\mathbf{V}_{gBest}$=$\mathbf{V}_n \times \frac{\mathbf{V}_{maxGBest}}{\|\mathbf{V}_{gBes}\|}$
9: **if** $\|\mathbf{V}_n\| \geq \mathbf{V}_{maxNeighbours}$ **then**
10: $\mathbf{V}_n$=$\mathbf{V}_n \times \frac{\mathbf{V}_{max}}{\|\mathbf{V}_n\|}$
11: Update the velocity as follows:

$$\mathbf{V}_n^{k+1} = \omega\mathbf{V}_n^k + \frac{c_1}{\Delta t} r_1(\mathbf{p}best_n - \mathbf{X}_n^k) + \frac{c_2}{\Delta t} r_2(\mathbf{g}best_n - \mathbf{X}_n^k) - \frac{\lambda}{\Delta t}\nabla(f(\mathbf{X}_n))$$

12: Update position as follows:

$$\mathbf{X}_n^{k+1} = \mathbf{X}_n^k + \mathbf{V}_n^{k+1}\Delta t \tag{12}$$

13: Repeat 3-10 until termination condition is met, i.e. when sufficiently close to destination.

This gives rise to two extreme conditions:

1) In the absence of repulsive potential fields, i.e. when the particle is far from an obstacle, the gradient term will be large and dominating.
2) In the vicinity of an obstacle, where stationary points exist, i.e. where the gradient is negligible in magnitude, the particle swarm dominates.

IV. Results

A. Classical Gradient Descent Algorithm

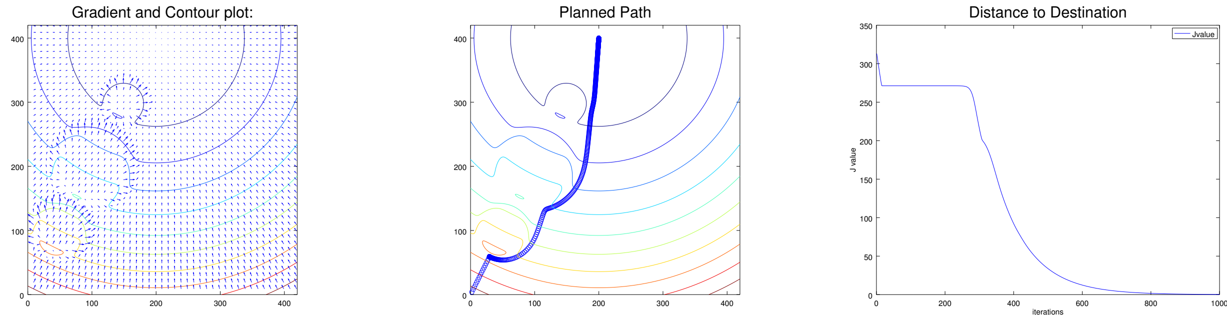
The results shown in fig. 2 were obtained using Octave, after 1000 iterations of Gradient Descent, with λ = 0.01. No clamps on velocity were imposed. It is clear that the suggested choice of repulsive potential function, has already solved a few problems associated with local minima [3]. The curve representing the distance to the destination, is labelled as 'Jvalue'.
The obstacles are placed at positions $\mathbf{p}_{obs1}$=[50,100], $\mathbf{p}_{obs2}$=[100,200], and
$\mathbf{p}_{obs3}$=[150,300], with radii 40, 60, and 80, respectively. In spite of obstacles on the course, pointing towards to the target, the planned path finds a way to circumvent them, presumably due to the choice of repulsive potential field. It can also be observed, that the distance to the destination remains visually, *"maximally-flat"*, in a small region between iterations 0 and 300. Indeed, it spends many iterations in the same configuration, yet never causes the distance to the destination to increase. The graph also clearly depicts the exponential drop in distance, characteristic of gradient descent on the paraboloid attractor function, and takes many iterations, to terminate the obstacle avoidance process.

B. Hybrid PSO-Gradient Descent Algorithm

Figures 3 through 5, obtained using Octave, display the various outputs that were obtained by using the proposed hybrid algorithm. The swarm comprises of 64 particles.
All the results were obtained after 1000 iterations of the hybrid GPSO algorithm proposed, and it can be clearly observed that the result shown in figure 3, achieves termination in approximately 150 iterations. The obstacle configuration is the same as in the previous case.
With the proposed algorithm, it is clear that convergence to the destination is obtained much faster. The graphs shown in figures 3 through 5, which display the variation of distance with respect to number of iterations passed, evidently shows the faster convergence obtained with the proposed algorithm. Careful analysis of the results reveals the following details:

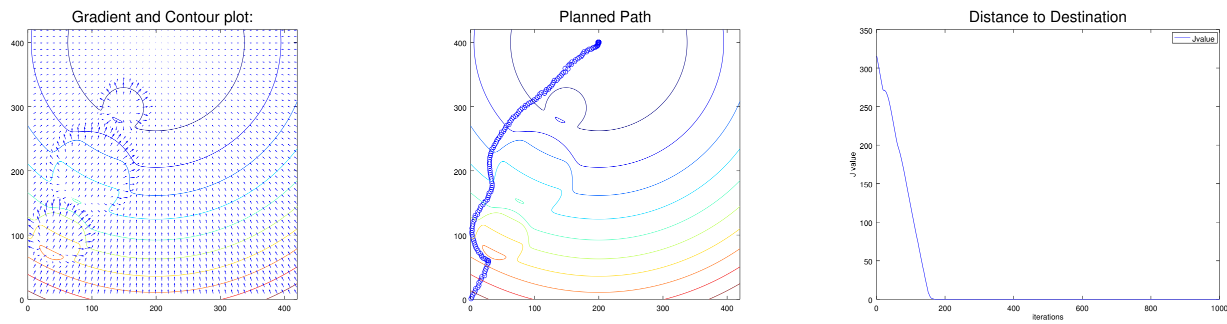
1) The number of iterations in which the distance to the target remains *"maximally-flat"* is negligible and almost unobservable.
2) The variation of distance, with respect to the number of iterations drops almost linearly.

It must be emphasised that by observing the results shown in Figures 4 and 5, lower time-steps, and higher maximum velocities will further reduce the termination time, of the hybrid-algorithm.
It is also clear from the above results, that the selection of the ideal time-step, apart from the various other parameters mentioned above, is also of paramount importance. It is clear that, choosing very small time-steps, may cause the algorithm to take far too much time, whereas larger values may also cause great errors in the process of obstacle avoidance.



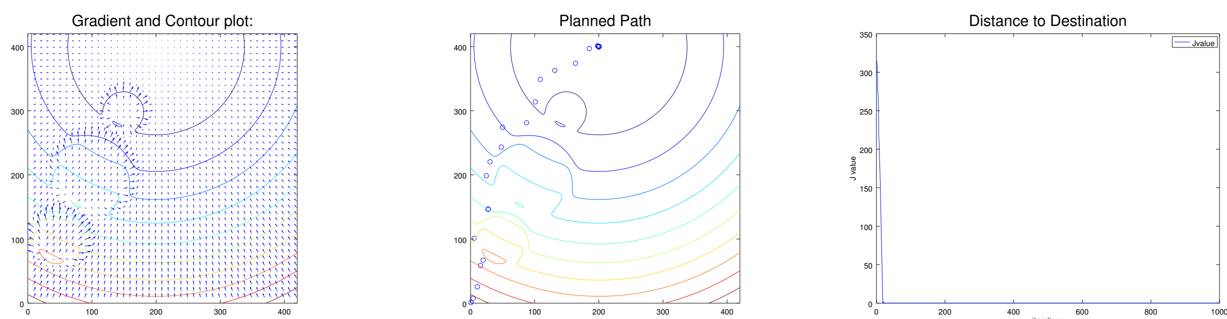
(a) (b) (c)

Fig. 2. Results of Gradient Descent, with λ=0.01



(a) (b) (c)

Fig. 3. Results of hybrid algorithm, with ω=1.61803398875, c1=1.61803398875, c2=1.61803398875, λ=0.61803398875, Δ t=0.01; maximum speed of gbest=180, maximum speed of neighbours=360



(a) (b) (c)

Fig. 4. Results of hybrid algorithm, with ω=1.61803398875, c1=1.61803398875, c2=1.61803398875, λ=1.61803398875, Δ t=0.01; maximum speed of gbest=1800, maximum speed of neighbours=3600

V. GPS Implementation and Experimental Results

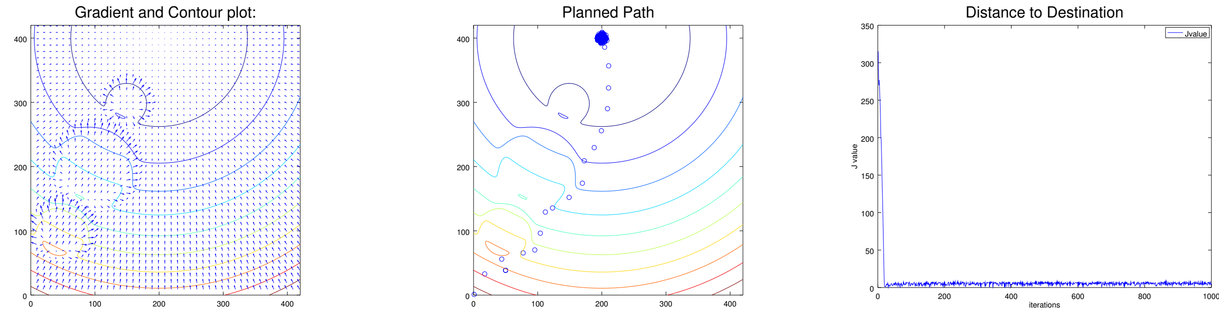
As mentioned earlier in section IV, the algorithm proposed, being general to any number of dimensions, can also be implemented for three-dimensional systems. The adaptation required to allow the hybrid algorithm to work with GPS coordinates, is a simple coordinate transformation. One might wonder, what need there is for such a transformation, when it seems sufficient at first, to merely make use of the three GPS coordinates, namely Latitude, Longitude and Altitude, as the vector-space to plan paths.

However, everyday problems, which may often span across merely a few kilometres in range, are often described by even smaller ranges of latitude, longitude, and altitude(to the tune of four of five places of decimal).

The reasons for employing coordinate transformations are two-fold:

1) Expanding the local-dynamic range of the GPS coordinates
2) Conversion to Cartesian bases for ease of analysis, and implementation

This paper will conform to the WGS84 standard of GPS coordinates, as it is one of the most common, yet simplest



(a) (b) (c)

Fig. 5. Results of hybrid algorithm, with ω=1.61803398875, c1=16.1803398875, c2=16.1803398875, λ=1.61803398875, Δ t=0.1; maximum speed of gbest=180, maximum speed of neighbours=360

(a) Original waypoints (b) Waypoints after obstacle avoidance

Fig. 6. Obstacle avoidance with GPS coordinates

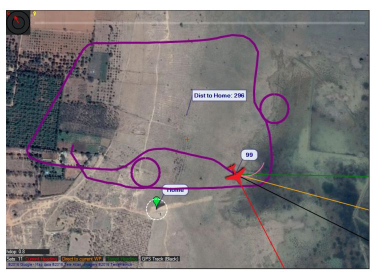


Fig. 7. Test-flight results of the UAV avoiding an obstacle

descriptions of geographic world-coordinates. For the purpose of conversion between GPS coordinates and local Cartesian coordinates, the open-source library GeographicLib [8] was used.

In order to obtain local-cartesian coordinates in an area, it is necessary to designate a home-location, by convention, as a reference point. By defining the obstacles, in terms of their bounding geometries, by using units of length such as metres, and position in terms of WGS84 GPS coordinates; we can obtain their corresponding local-cartesian coordinates in metres using the GeographicLib library.

The local-cartesian coordinates obtained are defined with respect to the centre of the earth, as the origin. Thus, the role of the home-reference point, which was mentioned earlier, becomes clear. These local-cartesian coordinates can now be given as obstacle, and waypoint inputs to the same obstacle avoidance algorithm, as proposed in section IV.

The flowchart as shown in Fig. 6, describe the overall procedure, as was discussed above.

Figures 7 and 8 display various outputs obtained, being displayed on the popular ground-control station for unmanned aerial vehicles, Mission Planner [9]. The results were obtained on a fixed-wing glider unmanned aerial vehicle. The paths generated are free of redundant points, unlike the raw outputs obtained from the algorithm described in the previous section. The Ramer-Douglas-Peucker [10] algorithm was used to do so. This step is important, so as not to encumber the auto-pilot with too many waypoints.

VI. Conclusion and Future Work

This paper presented a salient approach of combining both PSO and Gradient Descent for obstacle avoidance. The results of both the novel hybrid PSO-Gradient Descent approach, as well as for classical Gradient Descent were presented, and the clear novelty of the new approach in outperforming the classical approach was shown. The presented algorithm

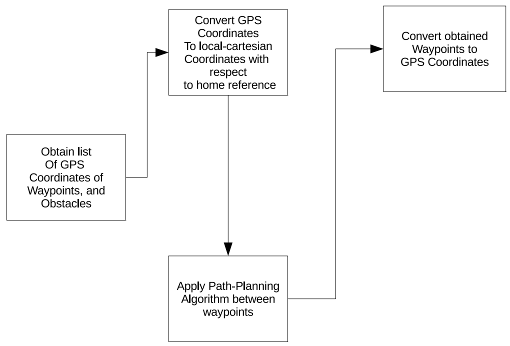


Fig. 8. Block diagram of GPS implementation of algorithm

exhibits faster convergence, in that it takes lesser number of iterations for navigating to the destination. Results with different control parameters were displayed and analysed. Subtle changes to the obstacle-avoidance process, on changing these control parameters have also been analysed. Results generated for GPS coordinates presented, which clearly reveal the efficiency with which the algorithm works. In future work, the shortcomings of the algorithm proposed will be acknowledged, such as accounting for non-circular obstacles. Dynamics aspect shall as be taken into account.

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