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Dynamic classification of ballistic missiles using neural networks and hidden Markov models

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ABSTRACT

This paper addresses dynamic classification of different ranges of ballistic missiles (BM) for air defense application based on kinematic attributes acquired by radars for taking appropriate measures to intercept them. The problem of dynamic classification is formulated using real-time neural network (RTNN) and hidden Markov model (HMM). The idea behind these algorithms is to calculate the output in one pass rather than training and computing over large number of iterations. Besides, to meet the conflicting requirements of classifying small as well as long-range trajectories, we are also proposing a formulation for partitioning the trajectory by using moving window concept. This concept allows us to use parameters in localized frame which helps in handling wide-range of trajectories to fit into the same network. These algorithms are evaluated using the simulated data generated from 6 degree-of-freedom (6DOF) mathematical model, which models missile trajectories. Experimental results show that both the networks are classifying above 95% with real-time neural network outperforming HMM in terms of time of computation on same data. The small classification time enables the use of real-time classification neural network in complex scenario of multi-radar, multi-target engagement by interceptor missiles. To the best of our knowledge this is the first time an attempt is made to classify ballistic missiles using RTNN and HMM.

1. Introduction

Classification of tactical and strategic missiles with reasonably accurate probability is of paramount importance for success of any air-defense applications. One of the key elements (challenges) in air defense is ascertaining which element in the threat cloud is the lethal object [15]. Air space during war typically consists of a combination of fighters, bombers, helicopters, transport planes, other air-crafts and ballistic missiles and cruise missiles. Since ballistic missiles (BM) have the capability to deliver weapons of mass destruction it is important to identify/classify these targets and take suitable measures to neutralise them. Fig. 1 shows one scenario where enemy missile is launched from point zero at *x*-axis and aims to destroy location at the range of 1500 km.

From the figure, it can be seen that ballistic missiles have three phases of flight, namely boost phase, mid-course phase and terminal phase. Boost-phase and early mid-phase are difficult to destroy as detection requires sensors in enemy aero-space or satellite intelligence, which is not possible and not done. This leaves late mid-phase and terminal phase as possible phases of interception of the enemy missile. Though the general policy of ballistic missile defense is to neutralise incoming threat at higher height and longer range so that debris falls away from intended impact zone [11], this is often not realised due to late detection and short response time of launch.

Another major element in the air-defense system is the Radar which has the multi-function capability of searching, detecting and tracking multiple targets. The radar provides data with higher rates to enable to compute area of impact and determine the time of launch by fire-control system. Electronically scanned phased array radars are highly reliable and provide multi-target tracking of tactical and strategic missiles [16]. The information provided by these radars can be used to classify the targets which are either direct measurement or derived parameters which includes position, velocity, accelerations, jerk factor, specific energy, altitude, radar cross section (RCS), etc.

Currently, the conventional methods using correlation based logic are able to deliver results up to 90% confidence level. The success of these statistical or template matching methods depends

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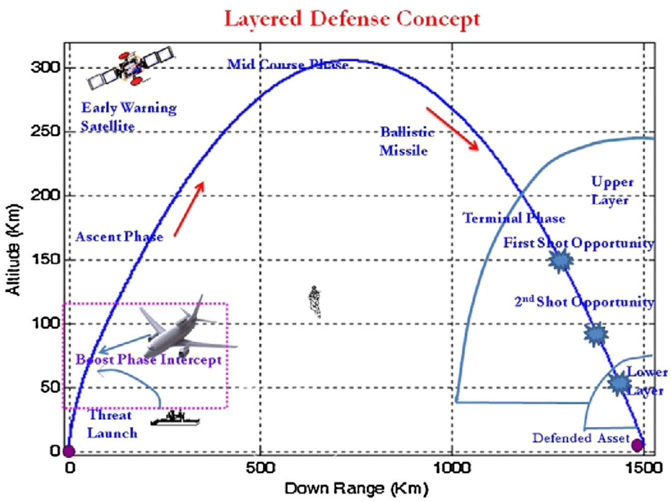

Fig. 1. Ballistic missile defense scenario.

highly on a-priori knowledge of range of values of parameters being used and the probability model used for the distribution of the parameter in problem space. More recent research activities in neural classification have shown promising alternative to conventional classifiers [18]. The different methods of target classification as discussed in [15,6,1] are based on off-line data for non-real time classification. Tamura et al. [17] introduced the idea of quantizers to show that a four-layered feed-forward neural network with $(N/2)+3$ hidden units can give any input–output relations with an arbitrarily small error for N samples of input vectors. Huang [8] extended the idea for utilizing the network for real-time computation and used numerous real-world regression data sets to verify the performance of their algorithm. Classification of motion trajectories using hidden Markov models [3] on recordings from visual surveillance is presented in [12]. Gaussian mixture-based HMMs for trajectory modeling and classification is described by Bashir et al. [2]. Silberman [15] describes a generic parametric approach to build classifier models, which is illustrated with an example of building a classifier for an infrared sensor. The drawback of that paper is that it does not refer to the time taken for classification. Classification of ballistic missiles during ascent phase using specific feature of perceived trajectory motion is addressed in [13]. This may not be true in all conditions as ascent phase detection and destruction of ballistic target has not been realised by any country. Moreover, in all realised systems, phase of detection and destruction is done during mid-course and early terminal phase and the classification technique proposed in this paper tries to achieve this end.

In this work, we deal with the problem of dynamic classification of ballistic missiles in real-time for air-defense application, which to the best of our knowledge has not been addressed before. The dynamics of ballistic missile can be broadly categorized into three phases of flight, namely boost phase, mid-course phase and terminal phase. It is also the case that the same missile can be fired to follow multiple trajectories. The classification of ballistic missile trajectory is a challenging problem due to its time-varying dynamics and short response time available for interception. Classification of variable-length trajectory and time varying dynamic attributes, which are important ingredients for ballistic missile classification, cannot be done using conventional techniques like neural networks, Bayesian or Kernel methods as mentioned above. To classify these variable trajectories, a moving window concept is used to restrict parameters in localised frame which in turn helps in reducing the problem to fit into the same network. To achieve this end we make use of real time neural network (RTNN) and hidden Markov model (HMM) using moving window concept.

The organization of this paper is as follows: problem formulation and need for trajectory classification is described in Section 2. Section 3 discusses details about approaches to real-time classification, algorithm used and the parameters taken for the classification. Section 4 details HMM model used for the application. Section 5 discusses results and timing analysis. Conclusions are given in Section 6.

2. Problem formulation – the need for real time classification

Ballistic missile is a missile that follows a sub-orbital flight-path with the objective of delivering one or more warhead to a predetermined target location. Ballistic missiles have powered flight, called boost phase, for initial phase and then it travels under gravitational law. During boost phase, vehicle has propellant and control capability to maneuver the vehicle. Out of its three phases of flight, as mentioned earlier, late mid-phase and terminal phase are aimed for interception. To have higher probability of interception, multiple shots of interception at various heights are planned in general.

It should be kept in mind that in air-defense application, `response time` to neutralize ballistic missile is dependent on many factors including range of radars for acquiring target of the given radar cross section (RCS), target velocity, preparation time of interceptor, velocity of interceptor, time of flight of interceptor, planned height and range of kill. The sequence of events involved in the interception of ballistic missile are detection by long range surveillance radar, assignment of interceptor by command & control system, computation by ground station to determine the time of preferred-launch and launch of interceptor missile. Table 1 shows various parameters of missile from 6-DOF simulation to arrive at response time. All time information given in the table is time with respect to launch of target missile for different class of ballistic missiles. Missile range in the first column is down-range it can travel. First five columns in the table relate to parameters of ballistic missile and last four columns enlist events related to interception. Apogee[1] and range of travel of ballistic missile depends on velocity, height and altitude of vehicle at the time of burn out of propellant. Burnout time is time at which propellant is spent out with respect to the time of lift-off of the vehicle. The launch bracket depends on time taken for preparation of missile and time required by interceptor to reach the kill height. Interceptor has variable flight duration depending on feasible height of kill. The time of preferred-kill is time at which interceptor can reach interception point based on its maximum capability and time at which it is launched to achieve preferred-kill is preferred-launch time.

A radar of specific acquisition range will detect a target within its capability of range acquisition with specified radar cross section. With radar placed at 50 km ahead of impact position of target and with a radar acquisition of fix range of 600 km, 6th column of Table 1 shows the detection time of the target missile of various ranges. Keeping range of radar constant and height of preferred-kill as 140 km, it is clear from the table that response time has decreased from 100 s for 600 km to negative for 2000 km class of missile and for a given interceptor flight time, target cannot be engaged at an altitude of 140 km or more. Thus, response time is very short and a real-time classification can play a vital role in initiating counter measures of launching interceptor missile against incoming ballistic missile.

[1] Apogee is the peak height obtained by the missile during its total flight.