Strategy Optimization of a Solar Car for a Long-distance Race using Big Bang – Big Crunch Optimization

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***Abstract*— In this paper, a new optimization approach based on Big Bang – Big Crunch optimization method to be employed in World Solar Challenge 2013 by Istanbul Technical University Solar Car Team is proposed. As much as the significance of renewable energy resources themselves, it is also important to optimally utilize them in an efficient way. World Solar Challenge is a biennially organized, 3021 km long race which serves a competitive ground for solar car teams from all over the world. Firstly, the solar car model which is subject to optimization is studied, and then the Big Bang – Big Crunch optimization method is developed for the proposed problem. After various simulation studies the optimal speed references are computed for predefined segments along the route. The obtained results are realistic and practical for World Solar Challenge.**

***Keywords*— Solar car, race strategy, optimization, Big Bang – Big Crunch, World Solar Challenge**

I. INTRODUCTION

The significance of renewable energy resources is evident considering the environmental effects which the earth is exposed to due to fossil fuel based energy consumption over the last century. According to the studies conducted, nine of the last ten years took place at the top of the list of warmest years on record owing to the global warming caused by the emission gas released during fossil fuel based energy generation [1]. By promoting sustainable resources such as wind and solar energy, the environmental pollution could be diminished. One of the most promising utilization for solar energy is the usage for transportation such as solar cars.

Istanbul Technical University (ITU) Solar Car Team was founded in 2004 not only to practically design solar powered cars, but also to demonstrate how efficient an electric car could be and to promote the importance of clean energy. With five solar cars produced and one being currently manufactured, the team is now focusing on World Solar Challenge (WSC) 2013 competition, which is the most prestigious solar car competition in the world. The length of the route is approximately 3000 km from Darwin, Northern Australia to Adelaide, Southern Australia. The car which achieves the highest average speed wins the race.

In order for a solar team to come in first place, solar car should be light, and aerodynamically shaped as possible and it should be equipped with high efficiency solar array, electric motor with a durable structural design and realistic estimation of state of charge for the batteries. Apart from all those specifications, energy management of the solar car throughout the race should be handled in a precise way that it considers varying parameters such as solar energy obtained, slope of the road and battery state of charge as well as the external limitations imposed by race and traffic regulations.

In literature, many research papers published by several solar car teams can be found. One of the first studies conducted in the field of solar car energy optimization is carried out by Aurora Solar Team in Australia which led the team to win WSC 1999 [2]. According to the study, the fundamental aim had been to determine a daily optimal critical speed that helps the team to cover the most distance possible while respecting the available sources of energy and external conditions using Hamiltonian Optimization Theory [3]. Another study is implemented by Solar Team Twente for the solar car SolUTra which participated in WSC 2005 and came in the 9th place. The study published in 2006 as an MSc project in 2006 by C. Mocking is based on dividing the whole strategy into sub-categories which are long-term, mid-term and short-term strategies. Gradient based optimization is employed to optimize the sub-strategies separately [4]. One of the studies that rely on classical analytical optimization methods is conducted by Graham S. Wright from University of Illinois for the solar car Sunraycer 95 participating in GM Sunrayce 95 in the USA. The study has brought a totally different point of view by determining short term strategies based on the weather conditions that the solar car may face to [5]. In addition to the studies conducted for Sunrayce 95, University of Illinois further enhanced the strategy to be used for the Sunrayce 97 competition. A model was formed with the current considered as the input and the output being vehicle

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velocity. The optimization objective was determined to minimize the final state of charge. Different velocity profiles are proposed for different scenarios such as constant conditions, acceleration from a stop, deceleration to a stop, climbing hills, descending hills and non-constant solar power [6].

II. LITERATURE SEARCH

In order to examine the studies implemented for similar solar racing strategy problems, a literature search is conducted. The HONDA Team created a more industrial and robust system with an Electronic Control Unit (ECU) in charge to run the Supervision Support System that implements the optimization task. Within the study carried out for WSC 1993, the objective is to keep the vehicle in the most efficient operating conditions as much as possible and to maximize the vehicle speed thereby. The strategies with respect to the weather conditions are categorized in three main groups as below:

- Low speed profile in case of cloudy weather, high in case of sunny conditions,
- High speed profile in case of cloudy weather, low in case of sunny conditions,
- Constant speed throughout the race.

It is concluded in the article that the most advantageous strategy to be followed is the second one which minimized the duration that the car is exposed to cloudy weather conditions [7].

Fig. 1. The fifth solar car of ITU Solar Car Team: ARIBA 5

In this study, a method which forms a basis for strategy optimization of ARIBA 5 shown in Fig. 1 for WSC using Big Bang – Big Crunch (BB-BC) [8] Optimization Method is presented. Recently, the BB-BC algorithm has found applications in many areas especially where the optimization problem must be solved in relatively small sampling times such as in fuzzy model inversion [9, 10], fuzzy model adaptation [11, 12] and online fuzzy rule weighting [13]. Moreover, in the optimization of highly nonlinear engineering problems such as controller design [14, 15], power systems control [16], and size reduction of space trusses [17], fuzzy controller optimization [18], learning of fuzzy cognate maps (FCM) [19, 20], this algorithm has been preferred because of its fast convergence speed and simplicity.

The aim of the study is to determine an optimal strategy to minimize the race duration while supplying the race regulations and the constraints imposed by the environmental conditions. In order to evaluate the effects of those components on race performance, a race model is constituted which is mainly comprised of solar car model and race specifications. For a solar car, the power consumption is based on the sum of the rolling resistance and aerodynamic drag which depend on the cruising speed of the vehicle as seen in (3) and (4). Hence, the solar car was driven at different constant speeds on a level road to find the power consumption out and justify the solar car model by determining the coefficients related to these forces of the vehicle. On the chassis dynamometer, the efficiency map of the motor and motor driver system is obtained by measuring the input and output power of the system.

III. A BRIEF OVERVIEW OF BIG BANG – BIG CRUNCH OPTIMIZATION METHOD

The reference speed values for the eleven segments specified along the whole route are optimized for the first time in literature using Big Bang – Big Crunch Method which is proposed by Erol and Eksin [8]. According to the benchmark tests conducted BB-BC has been compared with the combat genetic algorithms via several test functions such as sphere, Rosenbrock, step, ellipsoid, Rastrigin and Ackley based on the normalized performance measure which is depicted below

$$\log(f^*) = \log\left(\frac{f(\vec{x}^0)}{f(\vec{x}^*)}\right) \tag{1}$$

where $\vec{x}^0$ is a reference point with the vector value [10, 10, 10, …, 10]. For comparison, ameliorations are calculated for 30 trials by taking the average of the best fitness results into account. Considering the results the BB-BC method converges to the optimal solution much faster than the combat genetic algorithm [8].

The BB-BC Method is based on the theories about the formation of the universe consisting of two phases; the Big Bang phase which the dissipation of energy causes disorder and randomness and the Big Crunch phase that the particles produced in the Big Bang phase are pulled to each other so that an imaginative point representing the center of mass is determined. The center of mass, which is denoted as x^c is calculated using the formula:

$$\vec{x}^c = \frac{\sum_{i=1}^{N}\frac{1}{f^i}\vec{x}^i}{\sum_{i=1}^{N}\frac{1}{f^i}} \tag{2}$$

where x^i is a point created in an n-dimensional search space, f^i is a value of the fitness function for this point, N is the population size for the Big Bang phase. Afterwards, the Big Crunch phase is implemented in which a normal distribution operation is carried out in every direction that causes new off-springs to be generated around the previously calculated center of mass.

The algorithm may be summarized with the steps below.

1. Initial population with N members is created randomly. The limits of the space should not be exceeded during this operation.

2. The values of the cost function values are calculated for all the points.

3. The center of mass is calculated according to (2).

4. The new population is formed with new candidates gathered around the center of mass. It should be implemented by adding

or subtracting a normal random number which diminishes as the number of iterations grows. The new candidates are calculated with the formula:

$$x^{new} = x + \frac{l\,r}{k} \tag{3}$$

where l is the upper limit of the parameter, r is a random number and k is the number of iteration step.

IV. World Solar Challenge Simulation

BB-BC is a heuristic population-based search algorithm, thus an objective function is needed to estimate the results of the new generations. In this study, this objective function is preferred as a race simulation for a generic structure. Thus, a general race simulation is created in Matlab/Simulink environment and it is specified for ARIBA 5's parameters and WSC specifications, and it is named World Solar Challenge simulation (WSC simulation). There is not any significant curve during the route; hence, the lateral vehicle dynamics is omitted in this simulation.

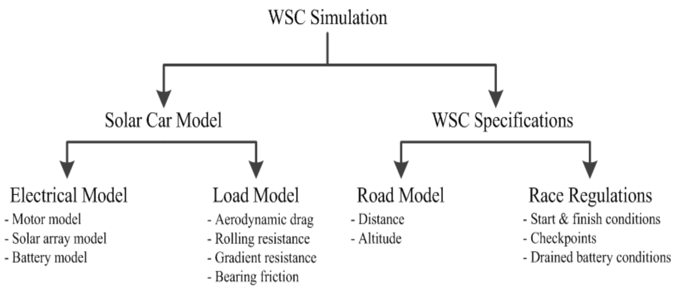

Fig. 2. Overview of WSC simulation

WSC simulation is divided into two sections: The solar car model and WSC specifications. The electrical and load models of the solar car constitute the solar car model. Further, the electrical model consists of the electrical motor, solar array and battery sub-models, and the load model includes the longitudinal dynamics of the solar car which are aerodynamic drag, rolling resistance of the tires, gradient resistance and wheel bearing friction. Besides, WSC specifications comprise the road model and race regulations. Since WSC simulation based on the longitudinal dynamics, the road model is formed by distance and altitude data. Additionally, start-finish conditions, checkpoints and drained battery conditions are considered due to the race regulations. The overview of WSC simulation is shown in Fig. 2.

TABLE I. Technical Specifications of ARIBA 5

ARIBA 5	
Production year	2011
Mass (kg)	185
Size (m)	5 x 1.8 x 1.1
Motor type	Axial flux permanent magnet
Solar cell type	Mono-crystalline silicon
Battery type	Li-ion
Vehicle body	Carbon-fiber
Aerodynamic Drag Coeff.	0.139
Rolling Resistance Coeff.	0.0066

A. Solar Car Model

Fundamental technical specifications of ARIBA 5 are presented in Table I. The solar car is driven by an axial flux permanent magnet motor mounted in the rear wheel of the car. In WSC simulation, the motor is modeled as a conventional brushless DC motor. R. Al Zaher indicated that the total efficiency of the motor and motor driver used in ARIBA 5 fluctuates about 92% for the operating speed rates; thus the efficiency is considered as constant in the motor model [21].

The required energy to complete the route is generated from the sun light with 22.5% efficiency using 392 mono-crystalline silicon solar cells which are located at the surface of the top shell. The efficiency and the total area of the solar cells are restricted by race regulations for WSC. Since the efficiency loss of the solar cells is caused by over temperature, the heating due to the sun light, weather temperature and the cooling due to the wind are included in the solar array model. Furthermore, a sun model is constituted considering the solar exposure database of Australian Government Bureau of Meteorology and the change of the solar array power for a sunny race day is collected from WSC simulation as shown in Fig. 3.

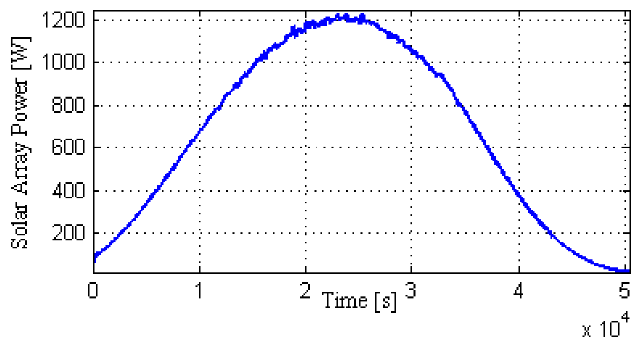

Fig. 3. Change of solar array power for a sunny race day.

The generated energy is stored at a lithium-ion battery when it exceeds the consumed energy. The battery is modeled using the charge and discharge curves regarding the battery cell. The bus voltage is calculated according to the electrical structure of the battery system. The general scheme of WSC simulation is shown in Fig. 4.

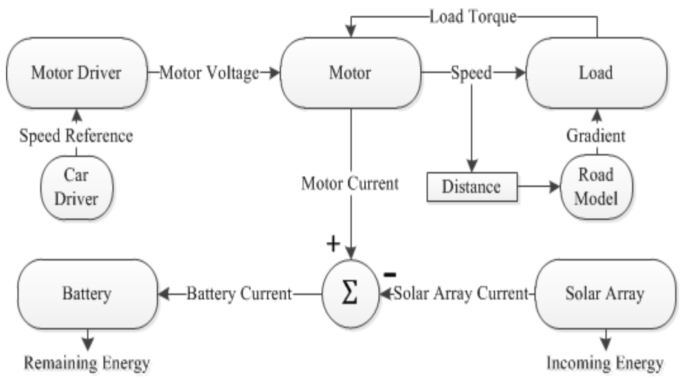

Fig. 4. General scheme of WSC simulation

The load model involves the longitudinal dynamics of the car which are aerodynamic drag, rolling resistance of the tires, gradient resistance and bearing friction. Aerodynamic drag force that the car is exposed could be expressed mathematically as

$$F_A = \frac{1}{2} \rho \, A_f \, C_d \, V^2 \quad (3)$$

where A_f is the frontal area, V is the vehicle velocity, ρ is the air density and C_d is the aerodynamic drag coefficient. Aerodynamic drag coefficient is a dimensionless quantity that is used to quantify the drag or resistance of an object in air. In addition to the drag force, another fundamental source for loss of energy is rolling resistance of tires. Rolling resistance, which could be formulized as in (5) is the force resisting the motion when a body rolls on a surface.

$$F_r = m \, g \, C_{rr} \left(1 + \frac{V}{161}\right) \quad (4)$$

The parameters related these dynamics such as aerodynamic drag coefficient, rolling resistance coefficient etc. are estimated and validated using test data. The power-speed curve is an important indicator of the efficiency of the car. Also it can be used for a comparison between the car and the model as shown in Fig. 5. It is seen obvious that the simulated power-speed curve cohere with the measured power-speed data.

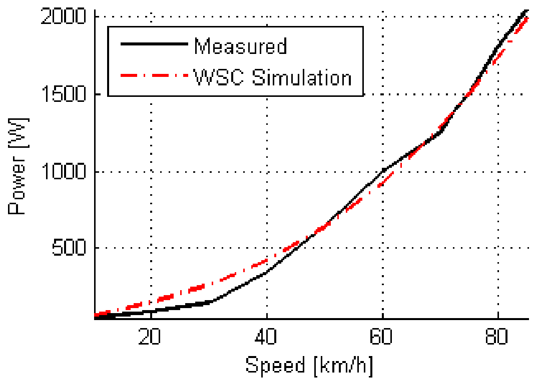

Fig. 5. Measured and simulated power-speed curves

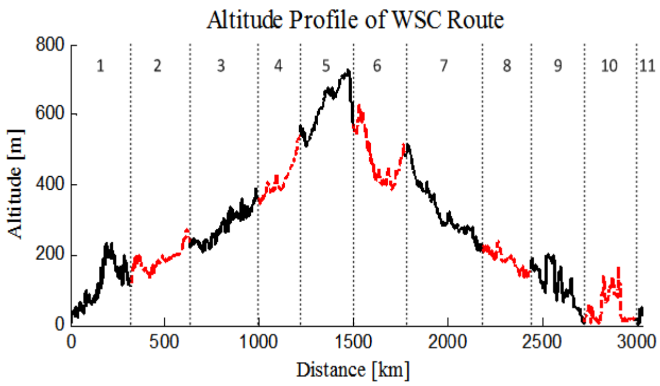

Fig. 6. The elevation profile of the route and the segments

B. WSC Specifications

The road model consists of gradient information through the distance and altitude data of the route released by WSC Committee. The altitude profile of the route is demonstrated in Fig. 6. In WSC simulation, the solar car begins to race from the start of the route, and it waits 30 minutes at 7 checkpoints and 10 minutes at 3 checkpoints, then the race ends at the finish point after 3021 km. If the race strategy determined wrongly, it would cause an energy shortage. In this situation, the solar car waits 10 minutes in order to charge its drained battery in WSC simulation.

V. Proposed Strategy Optimization Method

In this study, WSC route is divided into 11 segments regarding the checkpoints and the optimal speed references for these segments are computed using BB-BC algorithm. Fig. 6 illustrates the segments with different colors on the elevation profile of the route and each point between two segments represents a checkpoint.

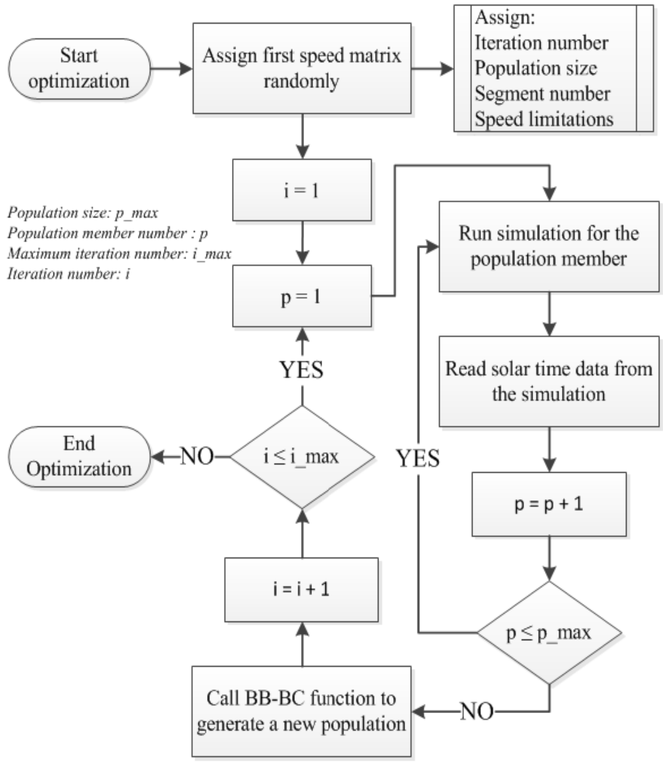

Fig. 7. The flowchart of the strategy optimization algorithm

A speed reference means the desired average speed in a segment; further, it is the only input of the WSC simulation and it is limited between 40 and 90 km/h for each segment in order to constrict the search space. There are 10 members in a population and every member is an 11-element vector because of the segment number. Hence, a population is a matrix with 10 rows and 11 columns and the first population matrix is every member of the current population, and then the total race time is fed back to BB-BC algorithm to generate offspring and the iteration number is increased by one. This evolutionary process continues until the maximum iteration number is reached and the total race time decreases throughout the new generations. The flowchart of the strategy optimization algorithm is shown in Fig. 7.Since the optimization process needs to be as fast as possible, the maximum iteration number is chosen as 25 and a parameter called smoothf specifies the number of iterations after which the search space shrinks to half is determined as 2 correspondingly.

A parameter regarding the weather which is multiplied with the maximum solar radiation is adjusted according to three main conditions which are cloudy, partly cloudy and sunny with the parameter values of 0.1, 0.5 and 1.0 respectively. In this study, it is supposed that the sky will be clear during the race; however, the weather conditions will be updated considering the daily and weekly forecasts for the race duration. It is obvious that in case of a more cloudy weather the average speed would decrease due to the less incoming solar energy. For the desirable weather scenario the evolution of the total race time throughout iterations is shown in Fig. 8. The cost function which is the total race time in this study decreases from 41.2 hours to 39.1 hours in the first ten iterations and remains constant, and then it diminishes to 39.05 in the 22nd iteration and does not change again. It means that if the environmental conditions such as solar exposure, wind speed etc. occur similar to WSC simulation conditions during the race, ARIBA 5 would complete WSC in 39.05 hours by cruising at the optimal speed profile demonstrated in Fig. 9.

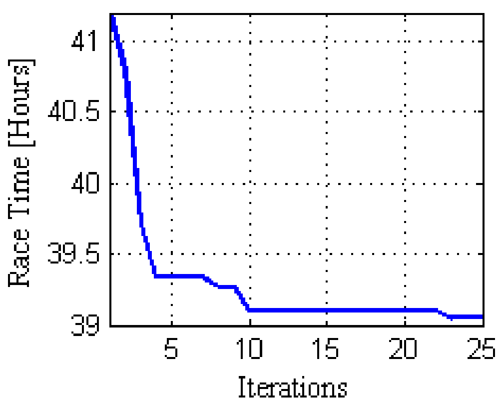

Fig. 8. Evolution of the total race time

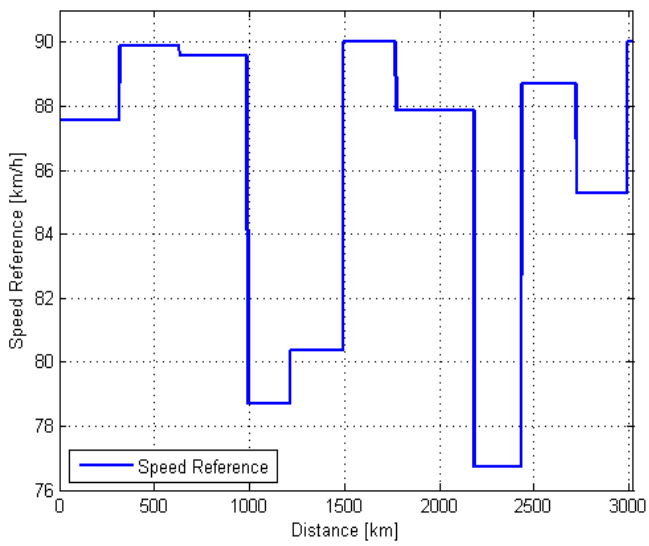

Fig. 9. Optimal speed profile

ITU Solar Car Team Strategy Interface which is designed using MATLAB Graphical User Interface (GUI) [22] environment is shown in Fig. 10. The GUI is created with the intention of easing online optimization carried out during the race. Its aim is to determine the optimized strategy for the remaining part of the route considering the current conditions. The inputs of the interface are the covered distance, remaining energy, day number and clock which will be entered during the race. Using the interface, the reference optimal speed may be determined anywhere and anytime on the race course for the next segment of the road. The optimization process is controlled by run and stop buttons. The optimal speed references for the current and next segments are demonstrated at the end of the optimization.

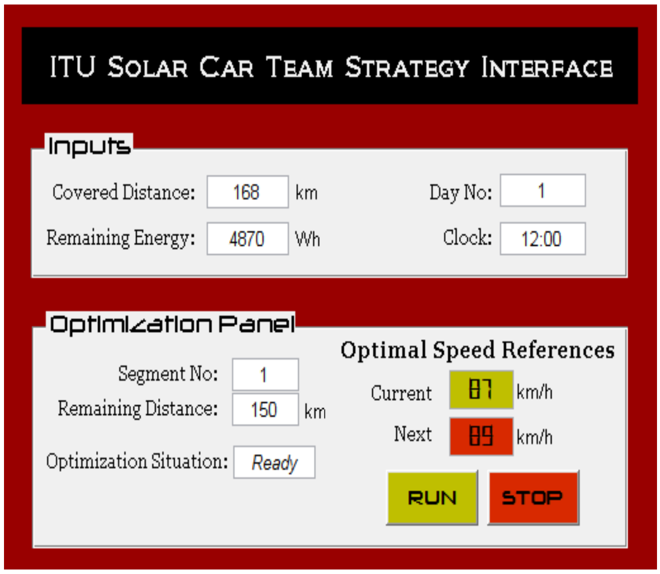

Fig. 10. ITU Solar Car Team Strategy Interface

VI. Conclusion

In order to achieve a satisfactory result in a competition for a solar car with high degree of specifications, the strategy implemented is also considerably important with the intention of revealing the best performance out of the solar vehicle. In this study, an effective optimization method called Big Bang – Big Crunch is presented for strategy optimization. For the simulations, the solar car model is obtained with its sub-components such as electrical model, load model, road model and race regulations along with comparisons made with road test results implemented. The results of the BB-BC based optimization which consists of reference speed values for the predefined segments of the race track are via various simulations. The obtained results from the simulations are studied by an expert group and found promising. With the optimization system constituted within the context of this study, ITU Solar Car Team anticipates to obtain a satisfactory result from World Solar Challenge 2013 with its latest vehicle ARIBA 6. In addition, a Matlab GUI is developed to be used to improve the performance of the proposed method during the real race.

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