AC 2012-5571: THE DESIGN AND DEVELOPMENT OF A SECURE INTERNET-BASED PROTOCOL FOR THE CONTROL OF A REMOTE SOLAR TRACKER

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INTRODUCTION

Solar energy is widely accepted as an alternative energy. Solar energy is captured by photovoltaic or solar cells, which is then converted into electricity. Most solar cells installations are attached to an immovable base, such as a roof top or ground base. The cells are generally pointed to the midday Sun position in the sky to yield maximum energy output from the cells. The problem with this arrangement is that a reduced amount of energy is produced during the early morning hours and late afternoon hours because the solar cells are not aligned to the Sun's position to receive the maximum amount of energy output. In order to receive the maximum potential of Sun energy, the solar cells must be constantly aligned to point directly at the Sun. The Solar tracking can be done manually, or can be also be done automatically by using a set of motors to move the solar cells and a group of light sensors to determine the Sun's position. The movement of the solar panels can be controlled remotely. A computer must be used to read the light sensors values, determine the Sun's position, and then issue commands to the motors to move the solar cells to face the Sun. An alternative to using light sensors to track the Sun's position is to use a solar position algorithm (SPA) to determine the Sun's exact position in the sky, as relative to the any given time and location on the Earth[1]. The current work focuses on two main aspects – development and implementation of solar tracking algorithm to increase the efficiency of solar cells by changing position of solar panels and software development for encryption and decryption of data that enables data transfer securely via internet.

There has been lot of work published in the area of solar tracking and some of them are discussed in this section. Work by Chong et al.[2] found that by using a Sun-tracking formula, they were able to track the Sun's position accurately and it was cost effective. They also found that while using light sensors (a closed loop system) gave a much better tracking accuracy, the system will lose its position if the Sun is blocked by clouds. There conclusion was that a Sun-tracking formula overall gave a significant improvement in the tracking accuracy.

The National Renewable Energy Laboratory (NREL) has an on-line solar position calculator for calculating the Sun's position give a local time, latitude and longitude[3]. In addition, NREL developed a code based on algorithm given by Reda and Andreas[1].

According to Kvasznicza and Elmer[4], a solar tracking system must be used to improve the overall efficiency of solar cell systems. They also reported that solar tracking systems in the Northern hemisphere regions, such as Great Britain, were less efficient because of a high diffusion of the solar radiation than in areas of the world that received a maximum amount of radiation and had low diffusion such as the Sahara in Africa. They proposed that more investigations were needed to determine the optimal amount of energy production for countries with different amount of solar radiation levels.

Some other notable works in the area of solar tracker algorithm and simulation tool development are by Rizk and Chaiko[5] and Sarker, Pervez, and Beg[6].

Rizk and Chaiko[5] implemented a simple solar tracker by only using a stepper motor and light sensor. Their work showed that by positioning a solar panel at right angle (perpendicular) to the Sun's ray, the energy collection efficiency of the tracker was improved. They reported an increase of energy efficiency of over 30% as compared to a fixed horizontal solar panel. Sarker, Pervez, and Beg[6] worked on a two-axis solar tracker built using a microcontroller, electronic sensor, and drive motors. They determined that their system was a flexible tracking system with low maintenance, and ease of installation and operation. They also found that by using computer software instead of mechanical parts their solar tracker would be more flexible for future development.

In the current research, the main objectives are:

1. Design the computer software to control the solar tracker (or multiple solar trackers) remotely via the Internet using the User Datagram Packets (UDP) protocol.

2. Design the communication protocol that will be used to send commands from the master controller computer to the remote controller computer.

3. Implement a secure encryption and decryption standard so that the communications between the master and remote computers will be secure and cannot be compromised.

4. Integrate a solar position algorithm into the master controller computer so that the azimuth and elevation position of the Sun can be determined for any location on the Earth given that location’s current time, latitude and longitude. This information will be transmitted to the remote controller computer to adjust the remote solar tracker to the current Sun’s position in the sky relative to the remote location on the Earth.

5. Simulate the physical hardware of the solar tracker by using animated computer software. The simulation will be used to test the operation of the whole system.

6. This work has an educational value towards understanding the algorithm for solar tracking and the encryption algorithm. The simulation software development is another aspect of the educational value to this project.

MATERIALS AND METHODS

Solar trackers can be single axle or double axle. In a single axle’s tracker, the tracker follows the Sun’s position along the east-west movement only, where as in a dual axle’s tracker, both the east-west and north-south position of the Sun are tracked through the day as well as during the year. In a dual axles tracking system, two methods must be available to rotate the platform surface to face the Sun at a perpendicular angle. This angle is necessary to receive the maximum amount of energy from the Sun. Generally two motors are used to rotate the tracker - the tilt motor used to rotate the platform in an east-west direction and the rotation motor used to track the Sun’s north-south position during the year. For precision tracking permanent magnet stepper motors are used whose rotation is controlled using suitable computer software. Stepper motors precise rotation angle may be easily controlled with computer software.

In order to determine the Sun's position in the daylight sky, electronic light detectors or sensors are used. A voltage is produced by the sensor which depends on the amount of light reaching the sensor. If less light is received by the sensor, this will result in less voltage output from the sensor, and this low voltage level could be used as a signal to rotate the platform position toward the Sun's position. In order to track the Sun's position in both the east-west and north-south direction, four light sensors are needed. A shadow block, located between the sensors, is used to cast a shadow on any cell that is not directly perpendicularly aligned to the Sun's position. Figure 1 is an illustration of a solar tracker light sensor assembly with shadow block.

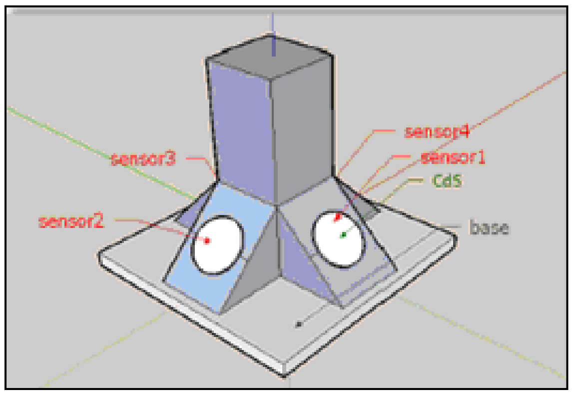


Figure 1. Solar tracker light sensor assembly with shadow block.

In order to track the Sun's position with the light sensors and stepper motors, a computer is used to sense the light sensors voltage level, and uses a predetermined algorithm to calculate the amount of movement via the stepper motor to supply to the tracker. If the computer is not located on site next to the solar tracker, then some means of communication is needed to connect the remote computer to the solar tracker. Figure 2 is a simplified diagram of the solar tracker system in this work.

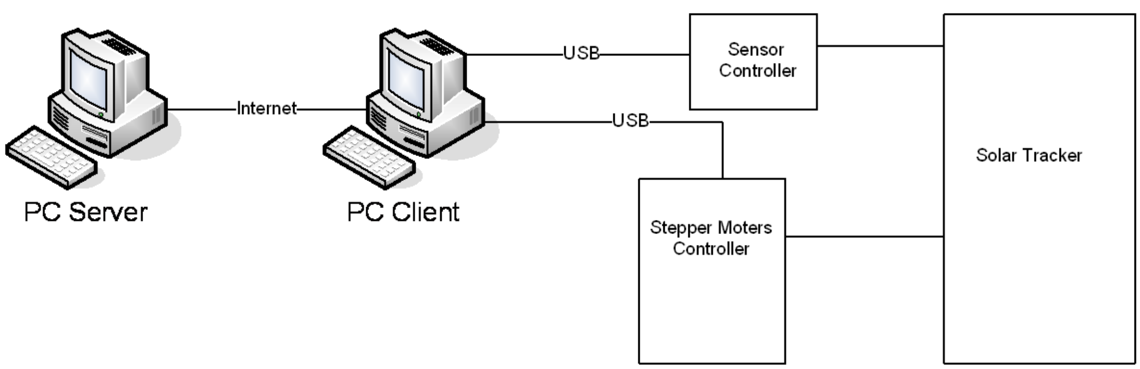


Figure 2. Simplified diagram of the proposed solar tracker.

Solar Tracker Software Design

In order to communicate with the solar tracker, a master/slave network is created with two computers. It is on this network that a custom protocol will be sent to the remote solar tracker. To avoid any outside or unwanted interference, the Advanced Encryption Standard method is used for both transmitted and received transmissions. However, the data must be checked to make sure it was sent or received properly. In order to check for errors in the protocols begin sent, a cyclic redundancy checker is used.

Cyclic Redundancy Check (CRC)

A cyclic redundancy checker (CRC) is an error detecting hash function code that is sometimes referred to as polynomial code. The CRC is generally 16 to 32 bits long and is used to check data for any error before and after transmission. CRC's are most commonly used to check data that is being sent over a network. For the solar tracker protocol used in this project, a 32 bit CRC is used to check the data packet being sent over the master/slave network for any errors[9].

Control Protocol

The custom packet used for command, control, and communication for the solar tracker consists of array of 96 bytes. The format for each byte as well as the purpose is listed in Table 1. Once data is added to the packet, it is encrypted and transmitted by using the UDP protocol for both the master controller and remote controller computers.

Item	Number Bytes	Meaning
TrackerID	1	Identifier number for the remote tracker
TrackerCommand	1	Command for tracker to execute
PrevTrackerCommand	1	Previous command executed
MotorID	1	Which motor to command
MotorEWPosition	4	East-West motor position
MotorNSPosition	4	North-South motor position
VoltageTracker	4	Voltage from movable solar cells panel
VoltageFixed	4	Voltage from fixed solar cells panel
SensorEast	1	Sensor to determine if motor at east home position
SensorWest	1	Sensor to determine if motor at west home position
SensorNorth	1	Sensor to determine if motor at north home position
SensorSouth	1	Sensor to determine if motor at south home position
Busy	1	Remote tracker is busy processing a command
Temperature	4	Temperature at the remote site
Elevation	4	Elevation of the Sun at the remote site
Azimuth	4	Azimuth of the Sun at the remote site
LatitudeDegrees	1	Site latitude in degrees
LatitudeMinutes	1	Site latitude in minutes

LatitudeSeconds	1	Site latitude in seconds
LatitudeDirection	1	Site latitude direction ad Equator
LongitudeDegrees	1	Site longitude in degrees
LongitudeMinutes	1	Site longitude in minutes
LongitudeSeconds	1	Site longitude in seconds
LongitudeDirection	1	Site longitude direction ad Equator
Time	8	Time at remote site
TimeDiff	1	Time different at remote site from control site
SiteName	14	Site name
Number	2	Current packet number
CRC	4	32-bit CRC error check for all data inside of packet

Table 1. Format and meaning for the solar tracker custom packet.

User Datagram Protocol (UDP)

The User Datagram Protocol (UDP) is a communication tool that is a part of the Internet Protocol suite. It allows computers on a client/server network a chance to communicate with each other by sending short layered messages and/or commands called packets. These packets or group of bytes that the UDP send are called datagram. UDP is a connectionless transport layer protocol, which means that UDP provides no reliability.

Table 2 below shows the format of the datagram which includes the source port which identifies the source Internet port address (IP Address), a destination port which identifies the destination IP Address, a message length field which indicates the length of the Dataram in bytes, including header and data, an optional 16-bit checksum over header and data, and the data bytes.

0 4 8	16 24 31
Source Port	**Destination Port**
Message Length	**Checksum**
Data	

Table 2. User Datagram Protocol (UDP) datagram format.

The UDP protocol is implemented as a class as part of the .NET framework and the Microsoft C# programming language standard[7]. In addition, sample code is provided on the website on how to use the UDP class.

Advanced Encryption Standard (AES)
Encryption and decryption are methods used to secure data that is transmitted during communication. Encryption places a code on the data before being sent to the client computer by the server. Once received by the client computer, the code is decrypted by using a key to decode what was originally placed on the data the first time. The Advanced Encryption Standard (AES) is a United States government standard algorithm for encrypting and decrypting data. The standard is described in Federal Information Processing Standard (FIPS) 197[8]. The AES algorithm is implemented as a class as part of the .NET framework and the Microsoft C# programming language standard.

RESULTS AND DISCUSSION

The software developed based on NREL's solar position algorithm[1] using C# language takes the typical inputs as shown in table 3.

year	4-digit year. Valid range 2000 BC to 6000 AD
month	2-digit month. Valid range 1 to 12
day	2-digit day. Valid range 1 to 31
hour	Observer local hour. Valid range 0 to 24
minute	Observer local minute. Valid range 0 to 59
second	Observer local second. Valid range 0 to 59
delta_t	Difference between earth rotation time and terrestrial time.
timezone	Observer time zone (negative west of Greenwich). Valid range -18 to 18 hours
longitude	Observer longitude (negative west of Greenwich) Valid range -180 to 180 degrees
latitude	Observer longitude (negative west of Greenwich). Valid range -180 to 180 degrees
elevation	Observer elevation [meters]. Valid range -6500000 or higher
pressure	Annual average local pressure (Valid range 0 to 5000 milibars)
temperature	Annual average local temperature [degrees Celsius]. Valid range -273 to 6000 degrees Celsius
slope	Surface slope (measured from the horizontal plane). Valid range -360 to 360 degrees
azm_rotation	Surface azimuth rotation (measured from south to projection of surface normal on horizontal plane, negative west). Valid range -360 to 360 degrees
atmos_refract	Atmospheric refraction sunrise & sunset (0.5667 deg is typical). Valid range -5 to 5 degrees
function	Switch to choose functions for desired output (from enumeration)

Table 3: Input Parameters for the Simulation

A computer simulation under ideal conditions was performed to determine the maximum possible energy output from a one square meter solar cells panel mounted in a fixed horizontal position in relation to the Sun and another one square meter movable solar cells panel mounted so that it was perpendicular to the Sun's position through out the day. The fixed solar panel was perpendicular to the Sun's position only when the Sun was directly overhead.

Two simulated locations for the experiment were selected, Morogoro, Tanzania and Huntsville, Alabama. Morogoro has a latitude of 6° 49′ 0″ S and a longitude of 37° 40′ 0″ E which is near the Equator. Huntsville, Alabama has a latitude of 34° 43′ 49″ N and a longitude of 86° 35′ 10″ W and is located in the middle part of the Northern Hemisphere of the Earth.

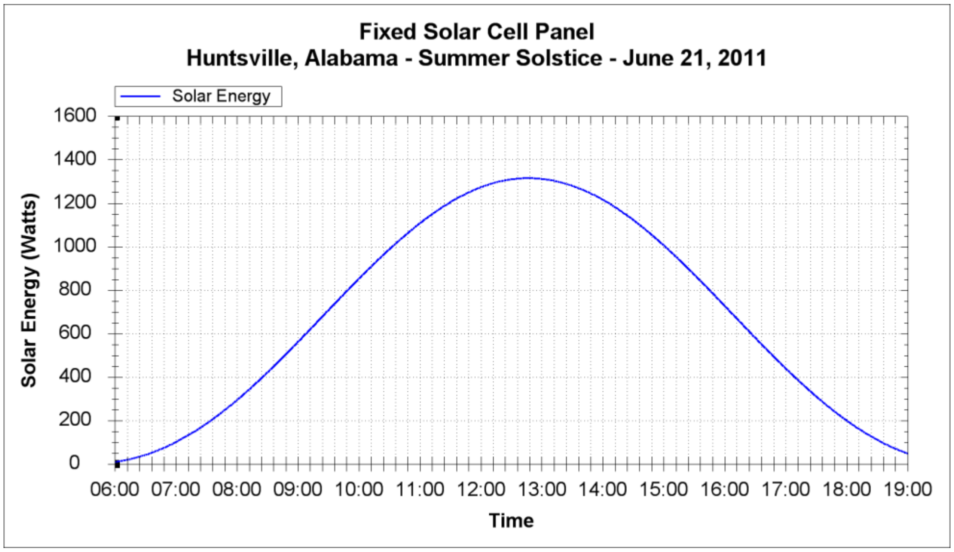
The four dates selected for the simulation were the Vernal Equinox March 20, 2011, Summer Solstice June 21, 2011, Autumnal Equinox September 23, 2011, and the Winter Solstice December 22, 2011. For each minute of the day, the total energy produced by both the fixed solar cells panel and the movable solar cells panel was calculated and recorded. Table 4 lists the average amount of solar energy produced for the two locations during the four dates for both the fixed and movable solar cell panels.

For the Summer Solstice (June 21, 2011), less solar energy is produced in Morogoro, Tanzania than in Huntsville, Alabama because during the Summer Solstice, Morogoro is experiencing its winter season while Huntsville is experiencing its summer season. For the Winter Solstice (December 22, 2011), Huntsville is experiencing its winter season while Morogoro is experiencing its summer season.

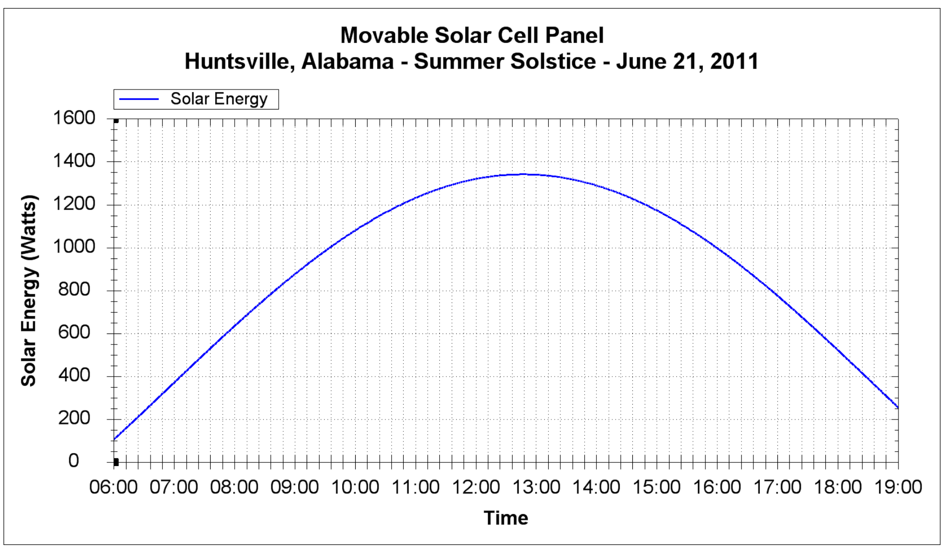
Location	Date	Average Energy Fixed Panel (Watts)	Average Energy Movable Panel (Watts)
Morogoro Vernal Equinox	March 20, 2011	668.63	857.50
Morogoro Summer Solstice	June 21, 2011	507.40	747.44
Morogoro Autumnal Equinox	September 23, 2011	667.83	856.85
Morogoro Winter Solstice	December 22, 2011	618.70	823.48
Huntsville Vernal Equinox	March 20, 2011	455.89	707.50
Huntsville Summer Solstice	June 21, 2011	630.25	825.62
Huntsville Autumnal Equinox	September 23, 2011	455.18	706.81
Huntsville Winter Solstice	December 22, 2011	192.31	461.42

Table 4. The average amount of solar energy produced at Morogoro and Huntsville.

Figure 4-1 (a) and (b) show the simulated solar energy collection versus time at Huntsville on the summer solstice day, June 21, 2011. Similar trends, but of course different magnitude plots were generated for Morogoro and all other days. Table 4 lists the average value over the day light period at two different locations, and at different times of the year.



(a)



(b)

Figure 3. Comparison of energy collection by (a) fixed and (b) movable solar cells

Master Solar Tracker Controller Simulation

The Master Solar Tracker Controller main function is to transmit, receive and process packets of information from the Remote Solar Tracker (RST) via the Internet using the UDP protocol. Because the packets of information are encrypted, the Master Solar Tracker Controller must first encrypt any out going packet and de-encrypt any incoming packets. The AES Algorithm is used for packet encryption.

The Master Solar Tracker Controller is able to transmit three commands to the Remote Solar Tracker. The commands are *Reset*, *Move_Motors*, and *Get_Status*. The *Reset* command will put the remote tracker in an initial state. It will transmit information in the packets to the Remote Solar Tracker Controller to initialize it site data structure. Table 6 is a list of data stored at the Master Solar Tracker Controller.

Item	Meaning
TrackerID	Identifier number for the remote tracker
TrackerCommand	Command for tracker to execute
PrevTrackerCommand	Previous command executed
MotorID	Which motor to command
MotorEWPosition	East-West motor position
MotorNSPosition	North-South motor position
VoltageTracker	Voltage from movable solar cells panel
VoltageFixed	Voltage from fixed solar cells panel
SensorEast	Sensor to determine if motor at east home position
SensorWest	Sensor to determine if motor at west home position
SensorNorth	Sensor to determine if motor at north home position
SensorSouth	Sensor to determine if motor at south home position
Busy	Indicate the remote tracker is busy processing a command
Temperature	Temperature at the remote site
Elevation	Elevation of the Sun at the remote site
Azimuth	Azimuth of the Sun at the remote site
LatitudeDegrees	Site latitude in degrees
LatitudeMinutes	Site latitude in minutes
LatitudeSeconds	Site latitude in seconds
LatitudeDirection	Site latitude direction ad Equator
LongitudeDegrees	Site longitude in degrees
LongitudeMinutes	Site longitude in minutes
LongitudeSeconds	Site longitude in seconds
LongitudeDirection	Site longitude direction ad Equator
Time	Time at remote site
TimeDiff	Time different at remote site from Master Controller site
SiteName	Site name
Number	Packet number
CRC	Error check

Table 6. List of Data Stored at Master Solar Tracker Controller

The *Move_Motors* command will cause the Remote Solar Tracker to move the stepper motors by the given number of positions. This will allow the remote tracker to track the position of the Sun. The *Get_Status* command will get the current status of the Remote Solar Tracker. This information includes the motors positions as well as the current solar cell voltage. Before the information is sent, the packet is encrypted by the remote site.

Remote Solar Tracker Simulation

The Remote Solar Tracker main function is to receive and process packets of information transmitted from the Master Solar Tracker Controller via the Internet using the UDP protocol. Because the packets of information are encrypted, the Remote Solar Tracker must first de-encrypt any incoming packets.

The Remote Solar Tracker is able to respond to three commands from the Master Solar Tracker Controller. The commands are *Reset*, *Move_Motors*, and *Get_Status*. The *Reset* command will put the tracker in an initial state. The *Move_Motors* command will step the stepper motors by the given number of positions. This will allow the tracker to track the position of the Sun. The *Get Status* command will send the current status of the Remote Solar Tracker to the Master Solar Tracker Controller. This information includes the motors positions as well as the current solar cell voltage. Before the information is sent, the packet is encrypted.

CONCLUSION

This research has shown that 40% or above increase in solar energy may be produced by using a movable solar cells panel as compared to using a fixed solar cells panel. In addition, a Master Solar Tracker Controller and a Remote Solar Tracker was demonstrated to allow for secure communications between the units via the Internet. This was accomplished by sending a custom unit of data or packet between the units encrypted the using the Advanced Encryption Standard. Software simulation of the MSTC and RST proved that the concept was feasible to implement.

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