Sensory Mapping

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Problem Statement

Dr. Miroslav Backonja, a neurologist who works in pain medicine at UW Hospital, has expressed the need for a more accurate method to measure the surface area of cutaneous sensory abnormalities. Currently, tracing paper is used to trace the affected area and a plenimeter is used to measure surface area. Dr. Backonja is looking to be able to measure surface area on contoured regions of the body in a more accurate and repeatable manner.

Design Motivation

Patients who suffer from various forms of neuropathic pain suffer sensory abnormalities due to damaged nerve fibers. This pain may become increasingly more intense over time and can prove to be debilitating in many patients. In order for this pain to be monitored, there must be a reliable way of tracking the area of each particular sensory anomaly. When it comes to managing such pain it becomes even more important to have an accurate recording of changes that occur due to treatments that are administered. The current method that clinics used to record the area of pain is to place tracing paper on the affected are as best as possible and trace the markings of abnormalities. This method becomes even more inaccurate when dealing with surfaces of the body such as an armpit or face, where paper cannot successfully cover the skin. Dr. Backonja has presented the challenge of finding a more reliable and accurate means for measuring the surface area of even the most contoured regions of the body in order to hopefully better treat patients with painful sensory abnormalities.

Background Information

Neuropathic pain presents as various forms of abnormal cutaneous sensations. These abnormalities can present as shooting pains, tingling, burning or numbness on the skin's surface (Pain 1). Neuropathic pain can be a result of many different illnesses or the treatments for these diseases. It can be painful diabetic neuropathy (PDN) or painful HIV-associated neuropathy (HIV-DSP) or it can also be a result of illnesses such as multiple sclerosis, cancer, and spinal cord injuries (Neuropathic 1). The pain intensity ranges from that of a sunburn to intense shooting pains. Due to the fact that neuropathic pain tends to be caused by other illnesses, the pain can prove debilitating on top of the symptoms from the disease the patient already suffers from.

Clinicians must monitor the changes in a patient's neuropathy in order to track the progress or effectiveness of various treatments. The way in which a doctor maps out the sensory abnormalities is to first use various brushes and tools to stimulate the skin and mark areas which patients indicate as abnormal. These markings are then traced over using tracing paper and a plenimeter is used to find the surface area of each affected area. To treat milder pain the patient may be given non-steroidal anti-inflammatory drugs while more severe pain may be treated with stronger painkillers such as morphine (Neuropathic 2). Management of the disease which is causing the neuropathic pain, such as diabetes, can help to alleviate some of the symptoms.

Competition

There doesn't appear to be a commercial product which deals directly with the problem of finding the surface area of a patient's skin. There is, however, a software program called BurnCase 3D which deals with burn victims (BurnCase 1). The software allows the doctor to trace on a 3D body the areas which are burned and differentiate between the severity of the burns. It then calculates the percentage of the body which is covered by each type of burn. The problem with this, however, the program doesn't provide any way in which to alter the given model. Without being able to change the body type or characteristics of the patient, tracing the affected regions on this model will not give very effective results. The only other programs which make 3D models from 2D pictures are very basic and don't involve dimensions.

Client Requirements

Dr. Backonja has specified several requirements regarding the design prototype. The first general area involves the patient and clinical usage. Given the fact that many of the client's patients have sensory abnormalities involving hypersensitivity, it is imperative that the proposed design does not induce excessive harm on the patient during clinical testing and usage. Accordingly, the prototype should also be conducive to the clinician who will be performing the test on the patient; portability and ease of use are important factors to consider. As a corollary, the procedure should be systematized, reducing clinician error as much as possible. Therefore, it is understood that the device should produce consistent, reliable results.

The second general area involves the actual function of the device. The goal of the device is to be able to calculate the surface area of the given body part in question. The accuracy of this calculation will be assessed relative to the current tracing paper and plenimeter method to calculate the surface area. The client has established an acceptable error rate of 5-10 percent. The device should also be able to store the collected data, preferably in a digital medium. Furthermore, the data should be visualized, possibly reproducing the surface in a digital manner. It will also be important to take programming into consideration, as the clinician's interaction with the device and is an integral part of incorporating digital media into the design.

The third and final general area involves cost. The client has established a preliminary budget of $500-1000. Additionally, the final prototype should be cost effective for the purpose of mass production, as the device is intended for clinical usage. Thus, the device will have to be produced at an affordable cost, without compromising the integrity of its computational accuracy and the reliability of the systematized method.

Data Analysis

The data will be collected as three-dimensional points of the form $P_i(x_i, y_i, z_i)$, representing the three spatial dimensions with all points being relative to some established fixed reference point (cf. *Design Alternatives*). The data will then be imported into MATLAB as three row vectors, each representing the three respective spatial dimensions. These three vectors will all have the same length, bearing the general form $\vec{v} = [\, v_1 \quad v_2 \quad \cdots \quad v_N \,]$ where *N* corresponds to how many points are collected using the device during a given trial.

The surface in question will be visualized using the Delaunay triangulation algorithm (Delaunay 1). This algorithm examines the (x_i, y_i) components of each point $P_i(x_i, y_i, z_i)$ and proceeds to determine that given point's planar natural neighbors. Using the Delaunay function in MATLAB, which takes (x_i, y_i) as its two arguments, an *m*-by-3 matrix is produced. This corresponds to the three vertices of the localized planar triangles that are created as a result of employing this algorithm. The surface is then interpolated using the trimesh and trisurf functions of MATLAB**,** which produce a surface having the functional form: $\left(x_i, y_i, z_i\left(x_i, y_i\right)\right)$. These plotting functions use the z values at each given point as one of their arguments. Another argument can be found after applying the Delaunay function to the other components of that same point and using the resulting triangulated matrix. This thereby determines to which height the vertices of the localized planar triangles should be extruded. It can be readily observed that the accuracy of the interpolated surface will be proportional to the number of points that are taken; this will have to be taken into consideration when systematizing the data collection procedure. Figure 1 shows two representations of a surface which was created using the Delaunay triangulation algorithm; one is a perspective using a mesh representation and the other a surface representation.

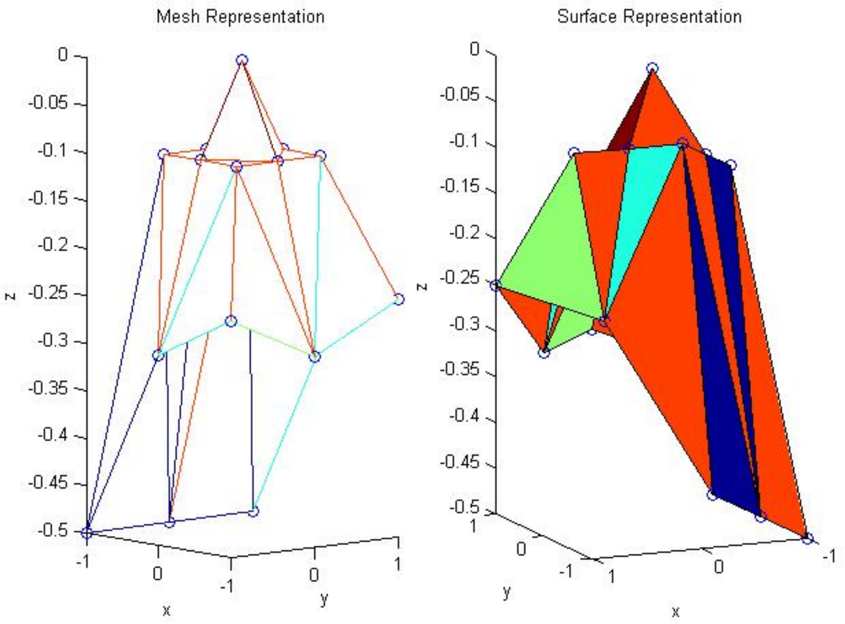

Figure 1: Three-dimensional surface representations (Delaunay)

The Delaunay triangulation algorithm will allow for the effective mapping of a multitude of surfaces on the human body, especially for various “difficult” regions (i.e. arm pits)—certainly more effectively than the current tracing paper method. However, there are limitations; given the fact that the interpolated surfaces, which are produced using the collected data points, have the functional form: $\left(x_i, y_i, z_i\left(x_i, y_i\right)\right)$. Namely, the algorithm will not likely be able to interpolate a surface which wraps around (i.e. from the chest, across the side, to the back). The reason is that this situation will produce ambiguous z data for certain points $\left(x_i, y_i\right)$, which are defined on both sides of the contour. This can be understood as overlapping or more precisely, projection through the surface on each side for one given point $\left(x_i, y_i\right)$). Thus, the algorithm will arbitrarily select a z data point for these troublesome points, producing an inaccurate interpolation of the surface. In such a case, this problem can be easily avoided by capturing the surface from different perspectives, each of which being well-behaved, and putting the entire surface together in a piecewise manner.

The surface area of the surface in question will be computed using Heron’s formula (Appendix A). Using localized triangles, in a similar fashion to the natural-neighbor triangles of the aforementioned Delaunay triangulation algorithm, surface area computations prove to be trivial for MATLAB. These computations will be performed using the triangle_area function, which represents Heron’s formula in MATLAB code, accepting a three-vector matrix corresponding to three spatial dimensions as its argument (Kroon 1). The formula (Appendix A) demonstrates the lack of point-interdependence in the computation, which is evaluated at each point individually thereby assuring the utility of using triangulation for the purpose of surface area computation. As with the interpolated surfaces, it is clear that the accuracy of the surface area computation will depend on how well the points and the resulting triangles will represent the actual surface in question. Thus, increasing the number of points will clearly produce a more accurate representation of the actual surface. Fortunately, the surface area computation unlike the surface visualization, which employs the Delaunay triangulation algorithm will be virtually unaffected by any given surface configuration. This includes wrap-arounds by virtue of the lack of point-interdependence in the computation. Thus, one of the primary goals specified by the client, surface area computation, will be easily accomplished using a relatively simple and straightforward procedure which employs localized triangulation.

Design Alternatives

Our three designs all use the same data analysis using the previously mentioned Matlab procedure to find the surface area and to generate a 3D surface plot. Therefore, our designs focused on obtaining coordinates in the Cartesian system of the area of abnormality. In all the designs the patient must remain stationary or data will be skewed because points will be shifted in relation to each other. For large areas, such as those that cover the chest around the side and to the back, multiple areas must be calculated and added together.

Active Infrared Motion Capture

The active infrared motion capture system involves infrared motion capture cameras (PhaseSpace 1) and an LED that emits light in the infrared spectrum at 850 nm, as seen in Figure 2. Two camera units would be needed, each unit containing two cameras. The four cameras allow exact triangulation of the LED in three-space. The LED would be made into a stylus with the LED at one end. The software included in the system (Master) tracks the LED by measuring the distance to each camera. This software then outputs the data into a file that can be converted to a text document with the Cartesian coordinates.

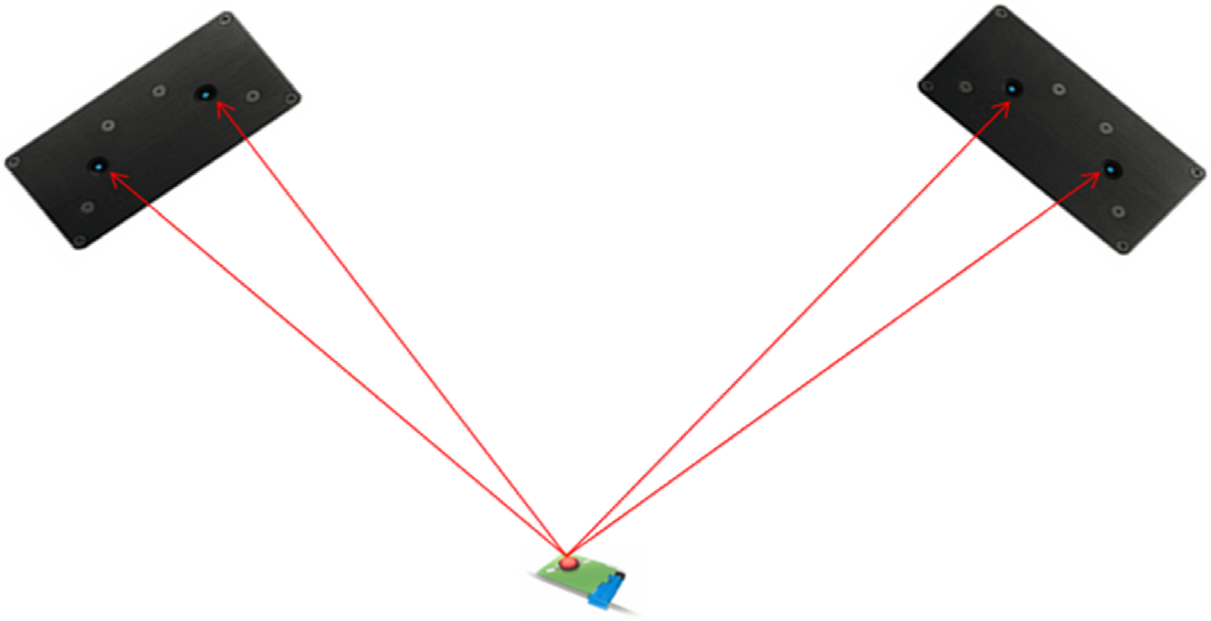

Figure 2: Active infrared system diagram

The active infrared system has two main advantages. The first of which is that it is very accurate. The cameras can measure distances with an accuracy of less than one millimeter. Also, with the active infrared system the collection of data points is quite easy. The system needs to first be calibrated after setup, but this process takes less than five minutes. After the system is calibrated, the clinician simply needs to outline the afflicted area with the stylus. This involves circling around the perimeter and moving the LED back and forth over the inside of the area to provide the points necessary to show the curvature of the surface (Figure 3).

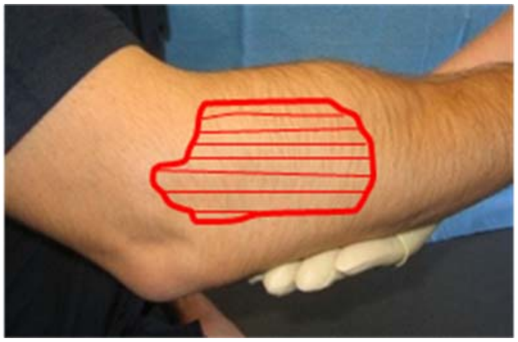

Figure 3: Example path needed to effectively map the area of sensory abnormality.

The active system carries some heavy. First and foremost, the cost of the system is staggering. A two camera setup including all necessary cabling and software would cost $17,560 after a 20% academic discount. The two other problems come from the LED. First, it must be pointed at the cameras at all times. If it were to be tilted away or obstructed from the view of the camera by clinician or patient, the system would lose track of it and data points would be lost. This would lead to an incomplete map and inaccurate surface area calculations. Second, the LED must be moved across the patient's skin in order to map the curvature of the area. This can be problematic for patients that are hypersensitive where the slightest touch can cause extreme pain.

Passive Infrared Motion Capture

The passive infrared motion capture system involves infrared motion capture cameras and a small reflective ball (Figure 4). Three cameras would be needed to determine the position of the ball in three-space. Each camera has a ring of infrared LED's that emit light. This light is bounced off the reflective ball and is captured by the camera at the center of the LED ring. The reflective marker would be mounted on the tip of a stylus similar to the active system to allow the clinician to easily map the area. The included (OptiTrack 1) and add-on software, Point Cloud Toolkit, allows exportation of the position of the marker into a file that can be converted to a text document with the Cartesian coordinates.

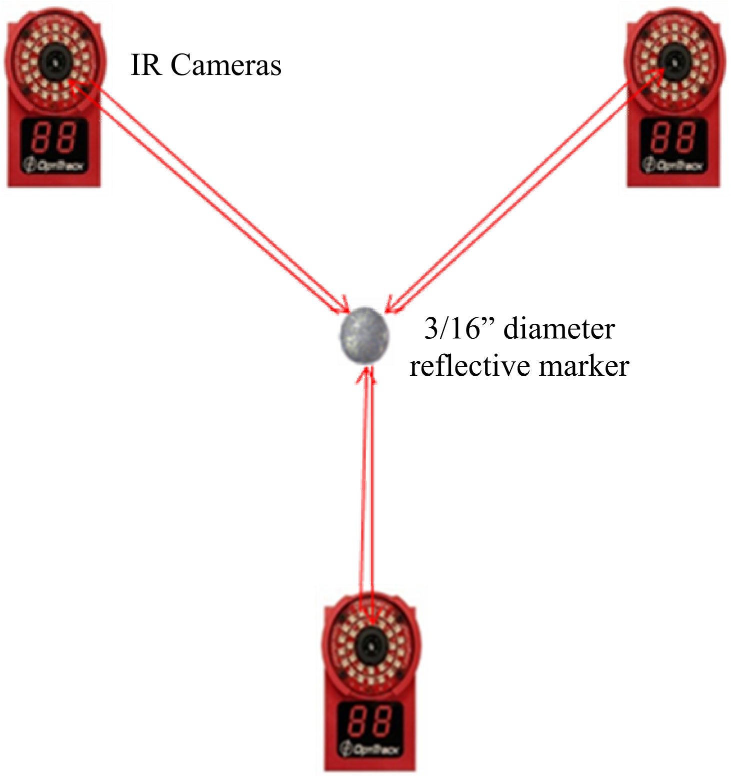

Figure 4: Passive infrared system diagram.

The passive system has the same advantages as the active system. It is highly accurate, capable of measuring distances with an accuracy of less than one millimeter. It is also easy to setup needing only a calibration to be ready to gather data. Once the system is set up, the afflicted area simply needs to be mapped in the same manner as the active infrared system. The key advantage by using this passive technology is the cost. For a three camera system, the minimum to map 3D points, the estimated cost is around $2,000. This includes the add-on software and necessary cabling.

The passive system also shares some of the same disadvantages as the active infrared system. While the cost is significantly less than that of the active system, it is still outside of our proposed budget. Also, the reflective marker still must be moved across the surface of the patient’s skin, which is a concern for patient comfort.

Laser Distance Meter

The final design involves using a laser distance meter. To gather the points, an arbitrarily chosen point on the region of interest would be selected as the “origin”. The distance would be measured to this point and saved for later. To determine the position of another point, the angles θ and Φ in the x and y directions respectively would be measured to the point as well as the distance to the point (Figure 5). Using the angles and the distances between the origin and the point being calculated, the Cartesian coordinates can be determined. By taking the origin distance times the sine of θ, the x coordinate relative to the “origin” can be found. The y coordinate can be found similarly by multiplying the point distance by the sine of Φ. The z coordinate can be calculated by using the cosines of the angles. The origin distance times the cosine of θ is subtracted from the point distance times the cosine of Φ. This process would be repeated for each pointed needed to complete the surface map.

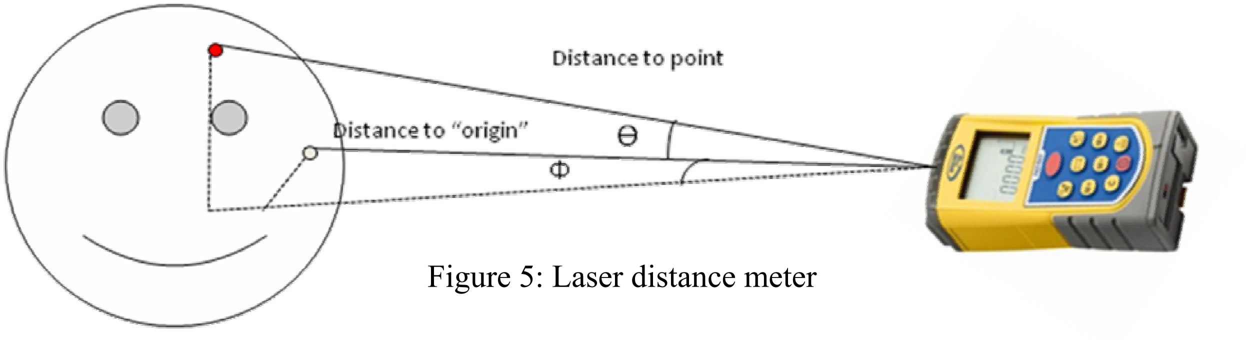

Figure 5: Laser distance meter

The laser distance meter has two advantages. The most significant is the cost. At only $130 (Spectra 1), it is well within our budget. The laser also risks no discomfort to the patient because it does not involve any patient contact.

This method has very big drawbacks, however. The biggest problem is the time and effort needed to gather the point data. Measuring the angles and the distances will take significant time. After being measured, there is no method to input it directly into a computer and would have to be entered by hand. The angle and distance data would then need to be converted into the points needed by Matlab to compute the surface area. Since the patient must remain still while the data is collected, the time needed to collect the data is unsatisfactory. The laser distance meter is also much less accurate than the infrared systems. It can only measure distances with an accuracy of plus or minus two millimeters. This is a problem when calculating the area of small regions of interest such as found on the face.

Design Matrix and Final Design

	Possible Points	**Passive IR**	**Active IR**	**Laser Meter**
Accuracy	15	15	15	11
Ease of Use	10	8	7	2
Time	10	8	8	2
Cost: Initial	15	7	3	13
Repeatability	5	5	5	3
Patient Comfort	10	7	7	10
Total	**65**	**50**	**45**	**40**

Table 1: Design Matrix

The three design proposals were evaluated using a design matrix, seen in Table 1. The two factors given the most weight were accuracy and initial cost, which were the two main specifications that Dr. Backonja stated. The laser meter method scored the highest in cost, as the expenses would only total around $130. The infrared systems are considerably more expensive, and therefore did not fare as well in the category. They are, however, much more accurate than the laser meter method. Measurements using the infrared systems produce results to within a millimeter, which falls well within the specified 5 – 10 % accuracy with respect to the current tracing paper method. Using the laser meter, although still fairly accurate, introduces the factor of human error into the process. The clinician must make certain measurements and calculations by hand, which also makes the method slightly less repeatable because the clinician would likely measure a little differently each time. If just one error is made in the entire process, it will throw off the rest of the measurements and calculations as well.

The two main categories that eliminated the laser meter method were ease of use and time. It would take hours and hours of time for the clinician to carefully make all the correct measurements and calculations, and the process would likely be very difficult. It is for this reason that the method is impractical for this application. The process will probably extend beyond Dr. Backonja, so it is imperative that the chosen method be relatively easy to accomplish. Also, the patient must not move, so anything longer than a few minutes would cause the patient discomfort. The infrared systems relay the information instantly, and one receives feedback extremely quickly. No extra work is required by the clinician.

Between the two infrared systems, the main differences were in ease of use and cost. The LED on the tip of the pen in the active system must always be directly facing the camera, and this makes the passive system slightly easier to use, although the reflecting ball still must be in view of the camera. The cost of the two systems, however, was the key point in determining the desired design. Research has proven the active system to be upwards of $20,000, while the passive system is obtainable for $2000. The active system is well outside of our budget, while we may be able to afford the passive system. For these reasons, the passive infrared system is our chosen design.

Future Work

From here, the first step is obtaining the infrared camera system. If this fits within our required budget, it will involve purchasing a system of three or four cameras with all the necessary components. If, for some reason, it does not fit within our budget, we will have to use a lab on campus which has the infrared system set up. After speaking with Dr. Backonja, though, it appears we will have the necessary funding to purchase the system. The next step will be to design and create the pen which will be used to trace the abnormal areas of the skin. This will include attaching a reflector ball to send information back to the cameras.

After setting up the system with the cameras and pen, we must work with MATLAB to perfect the algorithms used to map the surface in three dimensions and calculate the surface area. Since this application is intended for clinical use, the process should be made as simple as possible to perform. Therefore, much time must be devoted to systematizing the procedure. The clinician should be able to trace the pen along the affected areas and instantly view an image and a surface area value. After putting the whole system together, the final step will be testing, possibly with one of Dr. Backonja's patients. This will ensure that the process is applicable and meaningful in a clinical setting.

Potential Problems

One of the main problems that could result from the passive infrared system involves our budget. We were initially given a budget of \$500 - \$1000, yet three infrared cameras would cost around \$2000. If our budget is unable to be expanded, we will not be able to purchase the cameras and will resort to simply using a lab on campus. However, it appears at this point that our budget will be able to support the purchase of three cameras. Another problem is the fact that the patient is unable to move his/her body during the whole procedure. Because the process is relatively quick, this should not cause any discomfort to the patient. However, it does make it impossible to map two separate sides of the body because the pen must always be in the sight of the cameras. This could be solved by mapping one side of the body, saving the information, then mapping the other side of the body. The total surface area could then be easily calculated. Another option, if our budget was expanded even further, would be to purchase a fourth camera. When positioned correctly, this could potentially allow the clinician to map both sides of the body at once.

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Appendix A

$$A=\sqrt{s\left(s-\sqrt{\sum_{i=1}^{N}(x_i-y_i)^2}\right)\left(s-\sqrt{\sum_{i=1}^{N}(y_i-z_i)^2}\right)\left(s-\sqrt{\sum_{i=1}^{N}(z_i-x_i)^2}\right)}$$

where $s=\dfrac{\sqrt{\sum_{i=1}^{N}(x_i-y_i)^2}+\sqrt{\sum_{i=1}^{N}(y_i-z_i)^2}+\sqrt{\sum_{i=1}^{N}(z_i-x_i)^2}}{2}$, known as the "semi-perimeter"

Heron’s Formula