INTEGRATING LAND SURVEY DATA INTO MEASUREMENT-BASED GIS: AN ASSESSMENT OF CHALLENGES AND PRACTICAL SOLUTIONS FOR SURVEYORS IN TEXAS

by

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A Thesis Presented to the
FACULTY OF THE USC GRADUATE SCHOOL
UNIVERSITY OF SOUTHERN CALIFORNIA
In Partial Fulfillment of the
Requirements for the Degree
MASTER OF SCIENCE
(GEOGRAPHIC INFORMATION SCIENCE AND TECHNOLOGY)

August 2012

Acknowledgments

I would like to take this opportunity to thank the many individuals who devoted their time and efforts to complete this thesis research. Their continued guidance and encouragement helped me persevere through the challenges of research. First, I would like to thank my thesis faculty advisor Dr. Karen Kemp. Her infectious zeal and eagerness to help find the right answer was a driving force in the completion of my thesis. A special thanks to my other committee members Dr. Jordan Hastings and Dr. Michael Goodchild. Dr. Hastings initially planted the seed that challenged me to research measurement-based GIS. Dr. Goodchild, although not a University of Southern California faculty member and was only a few months from retiring, chose to aid my research and become a committee member. For the initial idea and willingness to be on my committee, I will forever be grateful.

A very special thank you to individuals I was introduced to along the way. From Esri, Brent Jones, Global Industry Manager – Survey/Cadastre/AEC. Thank you for the hours of phone conversation and once again taking the time to explain the Parcel Editor. Also from Esri, Tim Hodson, who also took the time and made an enormous effort to help with my research. Finally, a special thanks to Byron Johnson, GCDB manager in Nevada, for making the time for several phone conversations and providing publications regarding the GCDB and its functionality.

Table of Contents

List of Figures

Abstract

The land surveying community has discovered the economic benefits of managing their survey data within a single system and view a geographic information system (GIS) as a possible method of doing so. However, the traditional coordinate-based design of a GIS does not contain the means to retain or employ the use of original measurements collected by land surveyors, a legacy that has resulted in skepticism among the surveying community. Thus, if a land surveyor desires to manage surveying data within a GIS environment, that GIS should be a measurement-based GIS (MBGIS). This research describes a MBGIS based upon the rules and relationships of measured points within the metes and bounds surveying environment of the state of Texas. Since Esri's parcel fabric data model contains several characteristics that indicate it might be considered a measurement-based system, it is explored as a possible method to manage and retain the measurement-based elements of metes and bounds surveying within a GIS environment. This study concludes that although the parcel fabric model has limitations when compared to an ideal MBGIS, it does have the capability to manage metes and bounds survey data if proper preparation and management techniques are applied.

Chapter 1: Introduction

The practice of land surveying involves working with measurements observed on the ground to determine the boundary of a parcel of land (Robillard et al., 2003). In contrast, a geographic information system (GIS) in its traditional practice defines a grid coordinate system in which to locate objects for data analysis and visualization, often compromising the integrity of ground measurements for the sake of creating a homogenous product (Goodchild, 2002). There are many opportunities for surveyors to integrate their work into traditional GIS practices, often improving upon the quality of the GIS and further diversifying the role of a traditional land surveyor (Olaleye et al., 2011); however, even with the recent contributions, the GIS community continues to fall victim to skepticism from land surveyors because of its traditional coordinate-based approach and early attention on data quantity as opposed to data quality (Deakin, 2008).

In contrast to Public Land Survey System (PLSS) regions, Texas is a metes and bounds state, which does not require reference to a benchmark or the existence of a geographic coordinate database (GCDB) when performing a land survey (Stamper, 1983). As a result, Texas surveyors typically create several arbitrary coordinate systems at a local scale, which leads to a variety of coordinate datasets. As time progresses, some coordinate datasets are consolidated, but as a whole, survey data remains divided, creating the risk of duplicating field work and office research. As an employee of a land surveying company in Texas, I have witnessed a lack of understanding of these problems and the struggle to integrate numerous coordinate datasets into a central database to fully derive the benefits of the data. Considerable time is wasted researching and pooling data before a job can be completed. Most surveyors recognize that these problems could be eliminated by having an integrated system (Jackson & Rambeau Sr., 2007). They also recognize GIS as a popular solution, but have apprehension about the technology because early GIS practices were not focused on survey-grade accuracy (Sorensen & Wetzel, 2007). As a result, GIS technology has been viewed as complementary to but not sufficient for the profession (Deakin, 2008).

The initiative to integrate land survey data into GIS has been discussed heavily in trade publications such as *The American Surveyor* and *Professional Surveyor Magazine* and in many journal articles such as those noted above. Software vendors such as Esri, the developer of the popular ArcGIS software, offer industry solutions to implement survey data into GIS. Esri devotes a major section of their corporate website to the management of land surveying and cadastral data.[1] Often, however, the challenges of data integration and the issues of data representation are rarely documented since the usual solution is to purchase software and pay specialists to integrate data for surveyors.. Consequently, the end user fails to understand the technical aspects and issues involved in the integration process. Lacking this knowledge has caused skepticism in the surveying community, a profession built on knowledge of accuracy and error adjustments in space (Jeffress, 2005).

The concept of a measurement-based geographic information system (MBGIS), which stores and manipulates relative measures of distance and direction between points rather than absolute coordinates for them, was formalized by Goodchild (2002). The key

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[1] Source: http://www.esri.com/industries/surveying/index.html

benefits of a MBGIS are its ability to calculate error and propagate adjustments throughout the entire GIS database when a measurement changes. A traditional coordinate-based GIS does not have this capability. It attempts to correct local areas rather than adjusting the entire system, which may only make matters worse (Goodchild, 2002).

This research addresses the theoretical concept of managing metes and bounds survey data within a MBGIS. *If* metes and bounds data is managed within a GIS, then it *must* contain certain measurement-based characteristics for error analysis and have the ability to retain original ground measurements to integrate with new measurements obtained in the field. Section 2 of this document is a review of past literature that helps support the argument that a MBGIS provides a suitable format to manage metes and bounds survey data. Section 3 explores the design of a MBGIS that could be used to manage and integrate metes and bounds survey data. As a supplement to these background sections, a Glossary is included at the end of this document to insure that technical surveying terms are used and understood consistently throughout this document.

Although none of the concepts addressed in Section 3 are original, their inclusion here still serves a purpose by addressing issues that arise when integrating survey data into a MBGIS. Developing a MBGIS for a metes and bounds system offers unique challenges because survey terminology and methodology are different than in PLSS systems. Implementing the theory of MBGIS in the challenging survey environment of Texas will indeed create new methodologies and may encourage the management of survey coordinate datasets within a MBGIS. By incorporating measurement-based adjustments and data representation methods traditionally used by surveyors into the framework of a GIS data model, surveyors will become less apprehensive to use GIS as their primary means of storing and manipulating survey data.

Section 4 of this document explores the parcel fabric data model within Esri's ArcGIS software. As research to complete this study progressed, the most recent design of the parcel data model was discovered as a "best practice" attempt to incorporate and retain original measurements from which parcels were derived. The parcel fabric, the continuous surface of connected parcels defined by points and lines forming closed polygons, within the data model incorporates ground distances when assessing error in the overall coordinate model (Esri, 2011), which is a major characteristic of a MBGIS. This data model also integrates highly accurate geodetic control points in the fabric adjustment process, which is viewed as a successful method to integrate various coordinate datasets into a *single* measurement-based system.

As reported later in Section 4, a small dataset of metes and bounds data, taken from computer aided design (CAD) sources, was integrated into the parcel fabric to display how common surveying data sources can be accommodated. Control points were created in the fabric to illustrate the use of high-accuracy GPS technology within a surveying environment. Additional metes and bounds data was then added to the fabric and error adjustment processes were performed to explore the least-squares adjustment process within the parcel fabric.

The results of these assessments were then used to formalize a methodology to manage metes and bounds survey data within the parcel fabric. Section 5 illustrates different methods to consider if one were to use the parcel fabric within a metes and bounds surveying environment while maintaining the ultimate goal of administering survey data within a GIS: integration of data into one system.

Section 6 of this document discusses the limitations of the parcel fabric in relationship to the theory of a MBGIS. The coordinate-based design of the parcel fabric is beneficial in terms of the visual representation of metes and bounds survey data. Traditional GIS data visualization methods can greatly improve upon data representation methods used in traditional surveying software. A MBGIS can potentially be used as a dynamic tool to help determine boundaries as well as produce highly precise and accurate maps for users, ultimately diversifying the business opportunities for survey companies. However, there are still limitations to using the parcel fabric for metes and bounds survey data. Although the current fabric dataset integrates ground measurements into the system, the adjustment processes involving error are still performed within the coordinate system. This does not allow for error propagation on the measured data itself, a fundamental flaw of the data model when compared to the theory of MBGIS. As a final point, future considerations of system design within the data model to better incorporate the theory of MBGIS are mentioned.

Chapter 2: Review of Literature

Using measurements as the basic carriers of metric information is the key ingredient in the design of a MBGIS (Buyong et al., 1991). If methods for incorporating ground-measured data in a MBGIS can be easily understood, the surveying community may be more willing to use the robust set of tools within a GIS environment. However, before a theoretical model of a MBGIS for metes and bounds survey data can be formulated, there are several topics that must be explored. The purpose of this review is to provide background on the different themes that form the basis of this thesis research. The review is divided into four sections as follows:

1. *Land Surveying Background*: A basic discussion of land surveying concepts is provided, with primary focus on the semantics of metes and bounds surveying.
2. *GIS and Land Surveying*: Different methodologies of survey data integration into GIS, including the creation of the abstract map from original survey field notes for the General Land Office of Texas (GLO) and data integration into GIS from a computer aided design (CAD) environment are discussed.
3. *MBGIS*: The theory of MBGIS, its brief history, and examples of the use and evolution of MBGIS are explored.
4. *MBGIS for Survey Data in Texas*: The example of the geographic coordinate database (GCDB) as a MBGIS is explained, and parallels from the three sections above as well as the GCDB are drawn to form the basis of the conceptual model used in this research.

2.1 Land Surveying Background

Land surveying is defined as the art of measuring and locating lines, angles, and elevations of the surface of the earth, within underground workings, and on the beds of bodies of water (U.S. Department of the Interior, 1973). Land in the modern state of Texas was originally granted from the Mexican government and from the precursor Republic of Texas in a different fashion than in PLSS states. Instead of being granted sections and aliquot parts within a township & range cadastral system, Texans were granted large acreages called “leagues” consisting of 4,428 acres. A married man was granted an entire league, while a single man was given one-third of a league (Stamper, 1983). These grants, called abstracts, were given the name of the individual to whom the land was granted. Today, the abstract remains the basis on which land is sold and subdivided as metes and bounds tracts, defined as “…a description of real property that is not described by reference to a lot or block shown on a map but is defined by starting at a known point and describing, in sequence, the lines forming the boundaries of the property” (Robillard et al., 2003).

Because of the growth of technology in surveying, metes and bounds tracts have evolved into very precise and accurate depictions of ownership (Robillard et al., 2006). They began as describing tracts of land in relation to who owned adjoining properties (Stamper, 1983), but now consist of angles, distances, coordinate system references, and detailed monumentation of corners (Robillard et al., 2003). It is the evolution and legal statutes of metes and bounds surveys that form a semantic “rule guide” when surveyors determine boundaries. The role of a surveyor in Texas is to collect and measure evidence described in previous metes and bounds descriptions from the property boundary they are determining as well as from adjoining properties, and establish the description of the property being surveyed.

In Robillard et al. (2003, 2006), the authors discuss various scenarios of metes and bounds legal descriptions and the procedures surveyors must follow to define a boundary. Usually, each line segment in a metes and bounds description mentions an angular direction, a distance, one or more monuments representing the line segment in the field, and the adjoining property description. These items have different weights in the decision of the surveyor in determining a property boundary. It is up to the surveyor to determine the best evidence, but the order of importance is usually: monuments found and measured in the field, adjoining legal descriptions, and finally bearing and distance.

When performing a boundary survey, surveyors usually begin with a sketch of the property and adjoining properties they are surveying. This provides them with the distances and monument calls within the area so a field crew knows what to look for at each perceived property corner (Robillard et al., 2006). Once evidence is collected, the data is usually downloaded to a computer for boundary calculations. The surveyor checks measured angles and distances between found monumentation and interprets past legal descriptions in the area to determine the boundary and write a legal description of the property being surveyed. Collected data is commonly downloaded and manipulated in a CAD environment, where a robust set of coordinate geometry tools are used to check and calculate property corners (Olaleye et al., 2011).

No matter the amount of precision involved in the data collection process, errors in surveying still occur (Robillard et al., 2006). These errors fall under three categories: gross errors – blunders as a result of human error; systematic errors – errors within the system or technology being used; and random errors – all unaccounted for errors. The most famous method of error determination and adjustment calculation in surveying is the least-squares adjustment method (Mikhail & Gracie, 1981). Least-squares is a method of estimating values from a set of observations by minimizing the sum of the squared differences between redundant observations. This method is incorporated into most software packages used for surveying, including CAD software and GIS software like Esri's ArcGIS. The outcome of a least-squares adjustment in a computer environment usually involves the output of error residuals and can be visualized by error ellipses. These error residuals are associated with both measured points as well as interpolated boundary corners.

2.2 GIS and Land Surveying

The benefits of integrating survey data into a GIS is a well-documented topic that several different survey publications discuss on a monthly basis (see for example, *Point of Beginning* and *American Surveyor Magazine).* Most focus on the business benefits of having data in one database, and the advantages of base maps that offer vast amounts of property and land visualization information in one file (Jackson & Rambeau Sr., 2007). The ability of surveyors to overlay different GIS layers for visualization and management purposes does indeed give users an advantage (Zimmer & Kirkpatrick, 2009). There is no question that having files scanned, stored and linked to a GIS provides numerous advantages over traditional file storage cabinets and paper copies (Corbley, 2001). These initial practices of data management in GIS must be noted because their reliability and use would only be increased within a MBGIS. This section discusses a few examples of how survey data has been integrated into GIS as well as the skepticism that was created between the two disciplines.

Data is integrated into a GIS several different ways, usually based on explicit coordinates (Goodchild, 2002). This has traditionally been known as coordinate-based GIS, resulting in processed and interpolated data where the integrity of the measurements themselves is not retained (Goodchild, 2002). This coordinate-based methodology was used by the General Land Office of Texas (GLO) to create the abstract layer base map for the entire state. Abstract ownership maps created by the Tobin Map Company, which originally created the maps for oil and mineral leasing purposes (P2 Energy Solutions, 2011), were digitized and georeferenced to form the base abstract map in Texas (General Land Office of Texas, 2011). The inclusion of surveyor's field notes has made the original base map much more accurate, but its coordinate-based design remains the driving force behind the GIS. Some data within the GLO's base map is precise while some is not. The ability to determine the amount of error in the different regions of the abstract layer is not possible in the coordinate-based design (Goodchild, 2002). The GLO's base map stores and manages an enormous amount of survey data including links to original copies of abstract legal descriptions, different mineral leases, their surveys, and various other information such as submerged lands along the coast of Texas.

Since it is generally accepted that most surveyors have used a CAD environment to calculate and store collected data measured in the field, the integration of survey data from CAD into a GIS has become a common occurrence (Zimmer & Kirkpatrick, 2009). Esri's ArcGIS product has an entire toolset built to integrate CAD data. Sipes (2006) highlights the historical differences between CAD and GIS. He states that CAD has traditionally been used in architecture and engineering fields as a design tool, where GIS has been used as a cartography and spatial analysis tool. Another difference he mentions is that CAD is generally used on a project-by-project basis, while GIS is geared toward a longer period of time; although, there have been recent software releases that use CAD and GIS integration to build upon projects in the CAD environment (Carlson, 2011).

Sharing data between the two environments is usually done as an import where CAD data is georeferenced or projected into GIS (Zimmer, 2011). Zimmer and Kirkpatrick (2009) discuss integrating data using the Bureau of Land Management's (BLM) geographic coordinate data base (GCDB) as a control. This method involves the use of GCDB measured data to adjust GIS data, a technique that is improving the accuracy of GIS data in those states that use PLSS. However, no matter the methodology to integrate survey data into GIS, the fundamental design of a coordinate-based GIS is still intact, thus, from the surveyor's perspective, ultimately degrading the integrity of the data (Goodchild, 2002).

Advanced technology in the surveying fields has helped bridge the gap between the two disciplines (Greenfeld, 2008) and recent articles suggest a movement towards increasing the education of surveyors about the field of GIS. Felus (2007) discusses several different concepts of GIS that are essential for surveying education including how to integrate data into GIS for spatial analysis and data visualization purposes.

As technology and data integration has increased, the value of more accurate GIS databases has been noted (Jeffress, 2003). As stated before, skepticism in the surveying community arises from early GIS practices, which had a primary focus on getting data into a system with less attention on accuracy of the data (Sorensen & Wetzel, 2007). Deakin (2008) mentioned this as the reason why surveyors have always viewed GIS technology as only being “complementary” to their profession, and few had greeted its emergence with enthusiasm (Deakin, 2008).

However both Deakin (2008) and Sorensen and Wetzel (2007) state recent movement in upgrading accuracy of spatial databases has sparked interest in surveying professionals. Jeffress (2005) argues that the field of GIS needs surveyors because of their understanding and knowledge of accuracy and error budgets. Zimmer and Kirkpatrick (2009) also mention this in their article about improving GIS data accuracy using survey data, noting that certain methods for integrating data can result in more accurate and reliable GIS data (Zimmer & Kirkpatrick, 2009). Survey data has the potential to play a large role in making GIS databases more accurate and more reliable, but since it has been the tradition to integrate survey data into existing coordinate-based GIS databases (Goodchild, 2002), the integrity of the survey data too often becomes compromised.

2.3 Measurement-Based GIS

An early definition of a measurement-based GIS system comes from Buyong et al. (1991). Such a system uses measurements as the basic carrier of metric information. The authors defined the system as part of their conceptual model of a measurement-based multipurpose cadastral system. They mention flaws in the cadastral system similar to that mentioned in the section above, where measured data is integrated into coordinate data and integrity is often compromised. They further argue that even though data within a parcel cadastre is derived from surveyed legal descriptions, the implementation of the coordinate-based system is substantially different from the traditional method of surveying, where the relative positions between measured data is held in high regard.

The primary advantage offered by a measurement-based system is the ease of updating - where the existence and value of each measurement are independent of each other, and new measurements play a role in updating older measurements through least-squares methods. The authors also cite incremental implementation as an advantage to a measurement-based system—which is quite the opposite of many coordinate-based systems—providing economic benefits for the implementation of a MBGIS. The most important benefit is the continual improvement of accuracy based on measured data points.

Following Buyong et al. (1991), Goodchild (2002) coined the term Measurement-Based GIS (MBGIS), and distinguished it from the traditional coordinate-based GIS. He argues that when data is stored in a coordinate-based system, its position becomes absolute and fixed in space with no ability to correct or update the data without creating geometric or topological distortions. Therefore any error between the rigid objects could not fully be known. Contrary to the surveying community, Goodchild argues it is traditional practice within the GIS community to assume the user can know the exact location of objects in space.

Heo (2004) discusses the use of measurement-based data when building a successful temporal land information system (LIS). Since surveyors are the primary users of the system, basing the system on ground measurements is a necessity (Heo, 2004). He mentions four functional requirements to successfully incorporate measured data into an LIS: measurement data retrieval, automatic coordinate update, spatial data consistency checking, and blunder detection. These parts are similar to the architecture proposed by Buyong et al. (1991). Within a measurement-based system, the three types of errors—gross, systematic, and random (Mikhail & Gracie, 1981)—can be detected and visualized in relation to other measured data (Heo, 2004). The ultimate decision process of a surveyor involves the calculation of relative error between measured points on the ground (Robillard et al., 2003). A system that can visualize these points based on weighted controls and rules of methodology (Goodchild, 2002) are beneficial to the surveying practice.

Building a GIS based on measured data and retaining the functions and methodology of how the data was measured or derived, allows the possibility of incremental correction and provides the user with estimates of the impact of measured error, even when integrating data with different positional accuracy (Goodchild, 2002). Measured points are not necessarily stored as static coordinates in space; rather, their position is contingent upon their relationship with other measured points. After establishing a set of rules to determine interpolated positions between measured points, the means exist to detect and correct data that may be distorted due to errors in measurement (Goodchild, 2002). This is not possible in a coordinate-based GIS.

2.4 MBGIS for Survey Data in Texas

The section above mentioned the benefits of a system that can visualize error between measured points. Although this type of system has been achieved within a CAD environment for the surveyor, it usually occurs at a very local scale. Therefore measurements taken within a few blocks are retained in one file together, but have no bearing upon the next block over, because its measurements are stored in a different file. Some years ago Esri created an extension known as Survey Analyst that allowed for the integration and display of measured data in a GIS. Navratil et al. (2004), tested the capabilities of the Survey Analyst extension on cadastral data. The authors note the ability of this MBGIS to improve the accuracy of the system as more accurate measurements are placed within the system. They were able to adjust small parts of the system just as the concept of MBGIS suggests. Although there were parts of the software they did not like, they found the Survey Analyst extension to be a big step towards the implementation of MBGIS. The Survey Analyst extension is no longer in existence and has been replaced by the parcel fabric dataset and the Parcel Editor toolbar in ArcGIS version 10.

The geographic coordinate database (GCDB) is the BLM’s initiative to create a common coordinate database to reference within all federally owned lands (Wurm &

Hintz, 2003). The GCDB has also evolved into the closest example of a MBGIS for survey data that is available to the public. All surveyed data within public lands in the Western U.S. must use the GCDB as its coordinate reference (Zimmer & Kirkpatrick, 2009). With the development of the WINGMM (Windows-based Geographic Measurement Management) software package which is a part of the National Integrated Land System (NILS), the BLM has been able to integrate measured data into their coordinate database (Zimmer & Kirkpatrick, 2009). The measured data is used to estimate error on township and section corners from older surveys when technology and accuracy were far inferior.

New technology in the surveying field has given the BLM a chance to weight the different eras and methods of surveying into their system to better estimate and understand error within their GIS. Wurm (2007) tested the GCDB's ability to be updated with more accurately measured data in a study undertaken at New Mexico State University. He noted that the dynamic nature of the GCDB and its long-term maintenance in which new measurements are added will improve the spatial accuracy between points. As a MBGIS, the GCDB contains data whose location is established by its measured position relative to other points in the system; has an upgradable accuracy through some known function; and contains a set of rules to weight error within the different eras and methods of survey data collection.

A MBGIS in a metes and bounds environment can be an ideal method of storing and manipulating land survey data. Metes and bounds surveying contains a different set of semantics than that of the PLSS, but can still fit within a MBGIS framework because the weight of determination of a metes and bounds survey falls much greater upon found and measured monumentation in the field rather than the actual bearings and distances called in the legal description (Robillard et al., 2006). A set of rules can be established to determine and assess the three types of error involved in survey data collection. The incorporation of base map layers for enhanced data visualization and other survey-related management decisions would still be available, combining the traditional benefits of a GIS with the benefits of known error budgets of measured points in the system. Data can be managed in one database, where all measured data are integrated and measured points are continually updated to interpolate positions of other property corners between measured points with greater precision (Goodchild, 2002). In addition to being a data visualization tool, a MBGIS could be used to propagate error within survey data and could be used as a decision support system for a surveying company.

Chapter 3: Theoretical Model of MBGIS for Metes and Bounds Survey Data

There has been a significant amount of research performed in the arena of measurement-based systems. Section 2 did not explore work done by others before that of Buyong et al. (1991), and little work was mentioned since Goodchild (2002) defined the term MBGIS and argued its advantages over traditional coordinate-based practices. Since 2002 and especially since Buyong et al. (1991), both the GIS and surveying communities have seen technological advances in their fields. This research presents the argument that if metes and bounds data is managed in a GIS environment, the GIS must be—or closely represent—a MBGIS. Because such a GIS must contain measurement-based characteristics, the relationship between measured points that must be supported within the GIS is discussed. The MBGIS must also retain relationships between traditionally measured points and high accuracy control points established using GPS technology. The use of control points within a MBGIS for metes and bounds survey data is also argued. Finally, a relationship model of the measurement-based classes of a metes and bounds MBGIS is illustrated for the purpose of retaining original ground measurements and traditional survey error analysis.

3.1 Functional Requirements of MBGIS for Survey Data

A measurement-based GIS is defined as a system that "…provides access to the measurements *m* used to determine the locations of objects, to the function *f*, and to the rules used to determine interpolated positions" (Goodchild, 2002), where *m* are the measured locations themselves and *f* are the functions that link measured positions together. It also provides access to the locations, which may either be stored, or derived on the fly from measurements (Goodchild, 2002). In terms of surveying, the measurements *m* of points on the ground would be identified with coordinates through the function *f* which are the recorded angles and distances between points. Sometimes these angles and distances have been recorded by a data collector in the field and converted to an <x, y, z> coordinate in an assumed system (Robillard et al., 2003). Although the measurements are in a coordinate system, their original angles and distances are retained in a data file for three main purposes:

- To compare the relationship of points and apply the rules of metes and bounds surveying to determine the boundary of a tract of land being surveyed.
- To resume additional field work in the area and incrementally add more measured positions to a system.
- To perform least-squares adjustment processes to minimize error within a system.

Traditional surveying methodology in a metes and bounds environment uses ground measurements as the carriers of metric information. A MBGIS for metes and bounds data must also retain original measured angles and distances for the three purposes above. The concept of retaining ground measurements differs from that of coordinate-based GIS. Measured locations are traditionally converted to a system's grid coordinates and geometric constraints are applied to interpolated positions to ensure a clean topological relationship between the points, lines, and polygons of a cadastral system (Navratil et al., 2004). Within this process, the measured relationship between points becomes unidentifiable resulting in the inability to ascertain and correct blunders of measured points. Storage and access to measurements pertaining to the location of each point in a system is essential to the design of a MBGIS (Goodchild, 2002).

3.2 Establishment of Control Points

The practice of land surveying has traditionally relied on the storage of measured positions relative to each other for the purpose of error analysis (Mikhail & Gracie, 1981), and to interpolate positions between measured points. As GPS technology has been inserted into the functionality of surveying, the practice of incorporating absolute positioning methods with traditional surveying practices has become necessary (Olaleye et al., 2011). The advancement of GPS technology contributes to Goodchild's (2002) hierarchy structure within a MBGIS as the creation of a coordinate database or control network has become increasingly easier to accomplish. Positions established with great accuracy by GPS can be assumed to "anchor" the network (Goodchild, 2002). The establishment of a control network is usually well thought out in terms of geometric continuity of a service area.

The network of "anchors" is then used to link other measured points together. If measured points share a lineage, or are linked to the same control points within the network, it can be assumed there will be a strong correlation in errors between locations of the measured positions (Goodchild, 2002). Also, because all of these points would inherit the same error involved in the establishment of control points, the effect of that error between them is negated. Therefore one can conclude the coordinates of established control points can be absolute, even within a MBGIS, assuming the shared lineage of other measured points is known.

This approach is evident in GPS surveying using a Real Time Kinematic (RTK) network of base stations. Redundancy in the system is established through linking measured positions to multiple points in the control network so least-squares adjustments and error analysis can still be performed on the measured positions. As additional measured data is linked to the network, objects in space and interpolated positions between measured points move up the geodetic hierarchy in terms of accuracy (Goodchild, 2002). Figure 1 illustrates this concept.

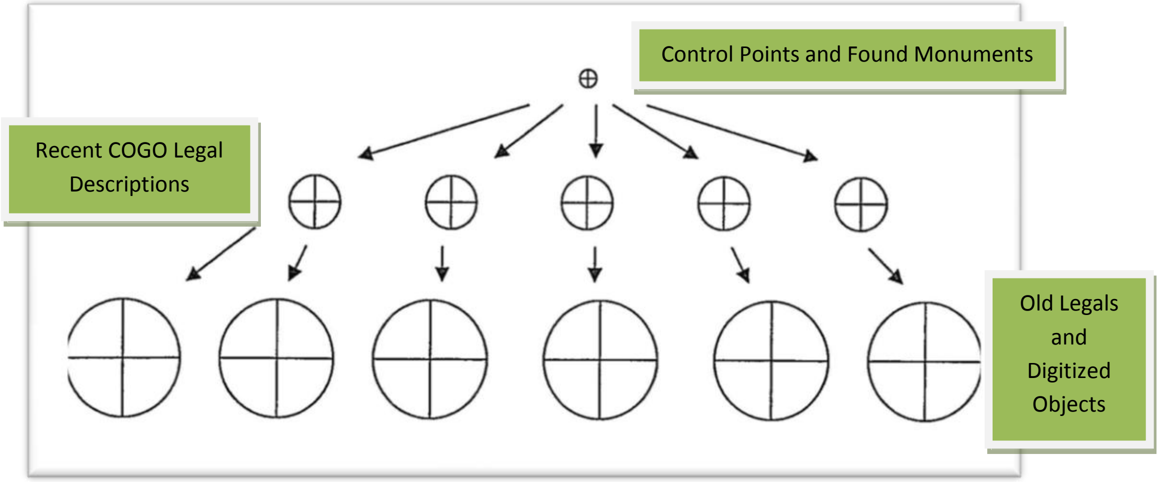

Figure 1 - Geodetic Hierarchy: This image, obtained from Goodchild (2002), displays the geodetic hierarchy of measured objects and the inheritance of error among positions that share control points. The boxes in green are examples of data within the surveying environment and how they would relate to each other in the hierarchy of measurement positions. In terms of error adjustments, different weighting methods would be applied to the different levels of accuracy.

An important goal for the surveyor managing data in a MBGIS is to implement a network where all measured positions in space (or at least property corners measured in the field) are at the top or systematically migrate to the top of the hierarchy of accuracy. This is achieved by adding more ground measurements to the MBGIS and linking them to multiple control points. Other property boundaries (either sketched from other surveyor's legal descriptions or digitized using aerial imagery), then assume their positions within the hierarchy of error within the MBGIS.

3.3 Upgradable Accuracy within a MBGIS

Interpolating positions of unfound or unmarked property corners is practiced by a surveyor in a metes and bounds environment on a daily basis (Robillard et al., 2006). The concept of a MBGIS states that as more measured positions are linked together and their method of collection is identified, the ability to interpolate unfound positions with greater accuracy occurs (Goodchild, 2002). A MBGIS for metes and bounds data must link measured data into one system to upgrade the precision of interpolated points represented in the system.

Because of time and money constraints, surveyors usually only establish the property corners of parcels that are necessary to determine a boundary. This frequently happens in metes and bounds surveying, especially when re-surveying smaller tracts of land that were once part of a larger tract of land. The measured relationship of each sub-parcel is incrementally established as the location of the larger parent tract is established. If all the points within the original parent tract share a network lineage, then the network of measured positions can correct for blunders within the original tract. The bounds of the original parent tract would traverse up the hierarchy of the MBGIS and the interpolated positions of unmeasured sub parcels would be more precise.

Consider Figures 2 and 3 as an example of upgradeable accuracy within a MBGIS. The field work completed to determine an accurate boundary survey was performed for the polygon labeled Survey 1. Only a portion of the original parent tract, represented as a thick blue line, was established to determine the location of Survey 1 (see Figure 2). There was enough evidence found to determine the boundary of Survey 1, but not enough to accurately interpolate positions of other sub-parcels within the same parent tract.

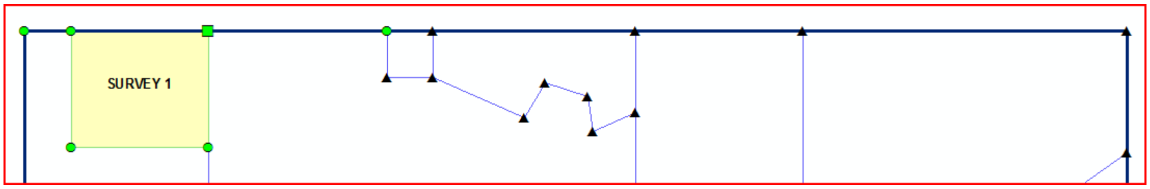

Figure 2- Interpolated Positions along a Surveyed Line Part 1: Work performed by a surveyor to determine the boundary of the polygon labeled Survey 1 as it lies within the larger parent tract (thicker blue line). The green circles represent found monuments and the green square represents a calculated monument based on the rules of metes and bounds surveying. Unfound corners within the parent tract (represented as black triangles) could not be determined with great accuracy because the bounds of the North line of the parent tract had not been measured by the surveyor, only enough work was done within time and money constraints to determine Survey 1.

Subsequently, points collected from Survey 1 were linked to new points found in an accurate boundary of the polygon labeled Survey 2 (see Figure 3). As a result, greater accuracy of points between these two surveys can be interpolated. Positions within the linked network migrate up the hierarchy of accuracy within the MBGIS. The two unfound corners along the North line of the parent tract, shown as large red circles in Figure 3, can now be determined with higher accuracy too.

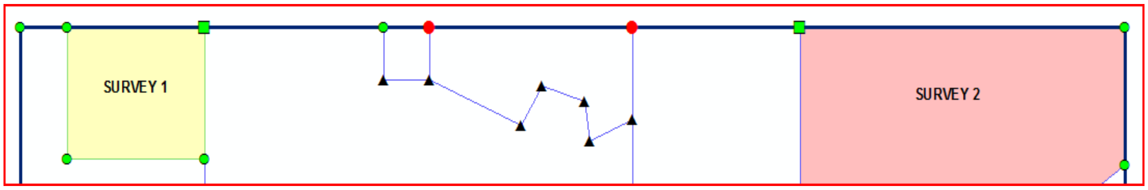

Figure 3 - Interpolated Positions along a Surveyed Line Part 2: The upgradeable accuracy of a MBGIS based on measured survey data and linking measured positions through a control network. Monuments found from Survey 1 were linked with monuments found for Survey 2 through common control points. As result, measured accuracies between the found monuments were upgraded as well as any interpolated position along the North line of the original parent tract. The red circles are still unfound corners, but can be interpolated with higher precision because of the linked measurements.

Because original measurements are presumed accessible in a MBGIS, it is possible to analyze the original positions measured in Survey 1 in terms of their relationship to positions measured in Survey 2, and how both sets of points relate to control points to further determine error within the system. The subsequent update of measured positions would result not only in interpolated positions gaining accuracy, but also originally measured positions being upgraded.

3.4 A Conceptual Model for Measurement Adjustment

The role of a surveyor has always been to accurately assess the boundary of the property being surveyed (Robillard et al., 2003). This is done by establishing and weighting the relationships between found and measured monuments in the field. A MBGIS to manage metes and bounds survey data must also contain methods of storing and weighting these relationships. Sections 3.1 through 3.3 above discussed characteristics of metes and bounds data that must be represented in a MBGIS and the use of absolute positioning of control points to establish a geodetic hierarchy of precision within a system of related data. This section integrates the parts by defining the required relationships between different measurement classes using only measured angles and distances to describe their relationship, thus creating a relational hierarchy.

Figure 4 below displays the relationships between the different measurement classes that establish the hierarchy within a MBGIS. Control Points (CP) are grouped in their own class and contain coordinates (x, y, and z) that are (assumed to be) absolute.

The Survey Points (SP) class contains points that are precisely measured or referenced in legal descriptions by other surveyors, such as property corners or street right-of-way monuments, and are used in the least-squares adjustment process. Because not all points in the SP are established with an equal amount of accuracy, an Accuracy attribute is used to weight measured points within the least-squares adjustment. This value ranks the relative accuracies of various surveying techniques. For example, a typical boundary survey might be assigned an accuracy value of 4 while a real-time kinematic (RTK) survey might be assigned a value of 2. These rank values could be provided in a reference table or a database domain.

A Data Source attribute of the SP also contributes to the weighting of points in the error adjustment process. This attribute ranks the confidence held in the accuracy of the data based on its source. For example, this can be used to indicate lower confidence in certain surveyors' measurements or uncertainty caused by missing metadata normally provided within a legal description or survey plat of a tract of land. Although this type of weighting is highly subjective, it must be included in a metes and bounds MBGIS because it is important to assess the existence of certain vital items such as bearing basis and scale factor that are frequently not reported by surveyors. A reference table or database domain can be populated over time to record the ranks assessed for specific sources and issues.

The relationship between pre-established control points and subsequent measured points is defined by an angle (usually azimuth angle in surveyors' raw data reports) and a distance. These two attributes can be calculated between any two points in a system of linked objects thus creating a lineage of measured relationships, creating a method in which points in the SP are adjusted in relation to their lineage with points in the CP. The lineage of the SP back to the CP is established by the Lineage relationship table, where a PointID is matched with a ControlID and their relative angle and distance is recorded. Each point in the CP can be related to one or more points in the SP and each point in the SP may be related to one or more points in the CP, but *not all* points in the SP will be directly related to points in the CP.

The Survey Points Association relationship table (SPA) retains measured angles and distances between points in the SP class. The difference in the SPA and the Lineage tables is that the former strictly interrelates survey points among themselves, without reference to any absolute coordinate in the CP. The angles and distances in these relationships are weighted through the attributes of the participating SP class and the weighting is used in the error adjustment process.

MBGIS Relationship Hierarchy for Land Survey Data

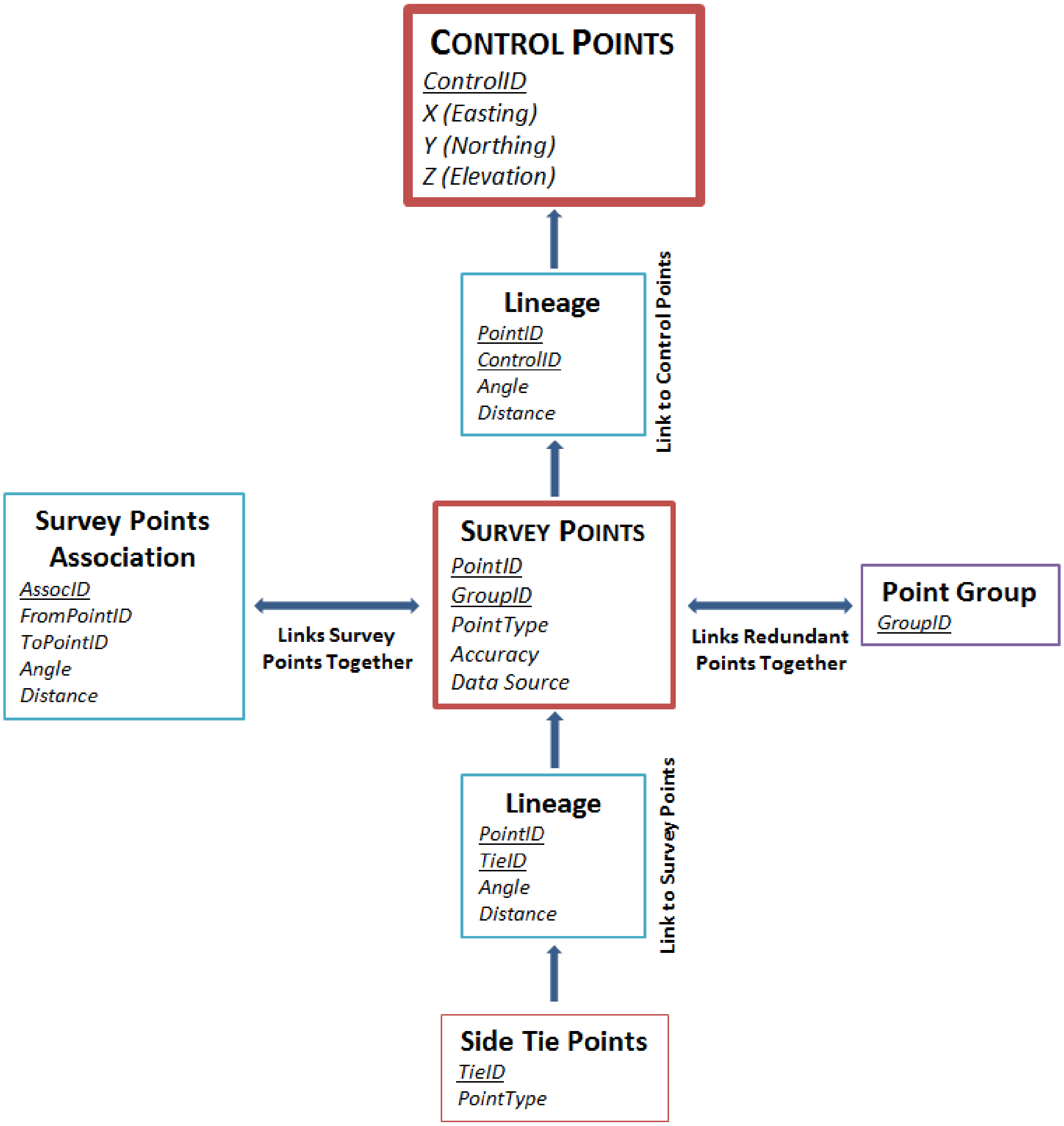

Figure 4 – MBGIS Relationship Hierarchy for Land Survey Data: Relationships between measured points and adjustments within a network would be achieved in a MBGIS using the measured angles and distances between points. Measured Points are weighted in terms of their accuracy and data source, and are adjusted based on their most likely position relative to control points. Obviously more accurate points within a system results in more accuracy overall within the network

about each single point that is represented redundantly in the dataset and links to the relevant SPs through GroupID.

Finally, the Side Tie Points (STP) class contains all other points within the MBGIS that are relative to the surveying environment, but not used in the least-squares adjustment process. Points in the STP include items such as house corners, fences, and driveways. The STP shares a Lineage relationship table with the SP in the same fashion the SP and CP share a lineage, where points in the STP adjust based on their angular and distance relationship to points in the SP in which a lineage is shared.

The relationships, classes and attributes shown in Figure 4 contain the elements necessary to execute a least-squares adjustment of measured points in space and give the surveyor the ability to retain the original measured positions. Neither of these characteristics, both of which are essential to building and managing a metes and bounds network, can be achieved in a traditional coordinate-based GIS (Goodchild, 2002). The least-squares adjustment would use angles and distances between the CP and SP stored in the Lineage relationship table, and relationships established by the SPA, to determine the most likely angle and distance between all points in space. The Accuracy and DataSource attributes within the SP weight each individual measurement within each PointGroup. Points in the SP with higher accuracy are weighted higher and therefore adjust less. Upgradeable accuracy would occur as more points are added to both the SP and CP classes and linked to the system.

Chapter 4: Esri's ArcGIS Parcel Fabric

The section above discussed elements of metes and bounds survey data within the theory of a MBGIS–as points in space interrelated by angles and distances between other points with some points having higher accuracy weight than others. The validity of a survey in a metes and bounds system is contingent upon the verification of angles and distances between monuments using ground measurements. Once again *system* is singular as the goal of a MBGIS is to integrate all possible measurements into one network (Buyong et al., 1991), a difficult concept when working with metes and bounds survey data.

Measurement-based systems have already been established within other computing environments such as CAD (Sipes, 2006). The advantage of a MBGIS over other systems is the ability to harness the attributes of traditional GIS functionality while still retaining original measurements for error adjustment, upgradable accuracy, and particularly reuse in the field. Esri has attempted to achieve these benefits with their release of ArcGIS 10 and the parcel fabric data model (Esri, 2012).

In this section, the Parcel Fabric data model is discussed as a "best practice" in terms of employing the measurements of survey data within a GIS environment. Since the Parcel Fabric data model is so extensive, only the parts pertaining to managing survey data and retaining measurements are discussed below.

4.1 Measurement Elements of the Parcel Fabric

The parcel fabric data model is a conceptual framework of the components of a parcel fabric dataset. The data model provides a schema for the creation of a geodatabase containing the various feature classes and relationships used to store information about parcel fabrics. The individual feature classes within a parcel fabric dataset are called parcel fabric layers. The parcel fabric data model contains several elements that relate to the measurement and error adjustment process. The phrase describing each element below was taken directly from Esri's web page describing the parcel fabric.[2]

1. Parcel lines, which store and preserve recorded boundary dimensions from legal descriptions and other data sources

For a surveyor, these data include lines imported from a CAD environment or legal descriptions involved in a deed sketch of an area surrounding a land survey performed by the surveyor. The parcel lines retain the original or published measured angles and distances between vertices. The retention of original measurements is key within a MBGIS, but it is also significant to note that these original ground measurements always remain unchanged, even after adjustment processes are applied.

A subtype of parcel lines is connection lines, which allow the user to integrate additional ground measurements into the parcel fabric. Connection lines connect points between parcels that are not adjacent. There are often times when legal descriptions reference a bearing and distance to another monument or property corner that is not adjacent to the tract of land (Robillard et al., 2006). This ground measurement can be retained in the parcel fabric through the use of connection lines. Figure 5 displays a connection line shown on a survey plat.

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[2] Source: http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/What_is_a_parcel_fabric/008500000002000000/

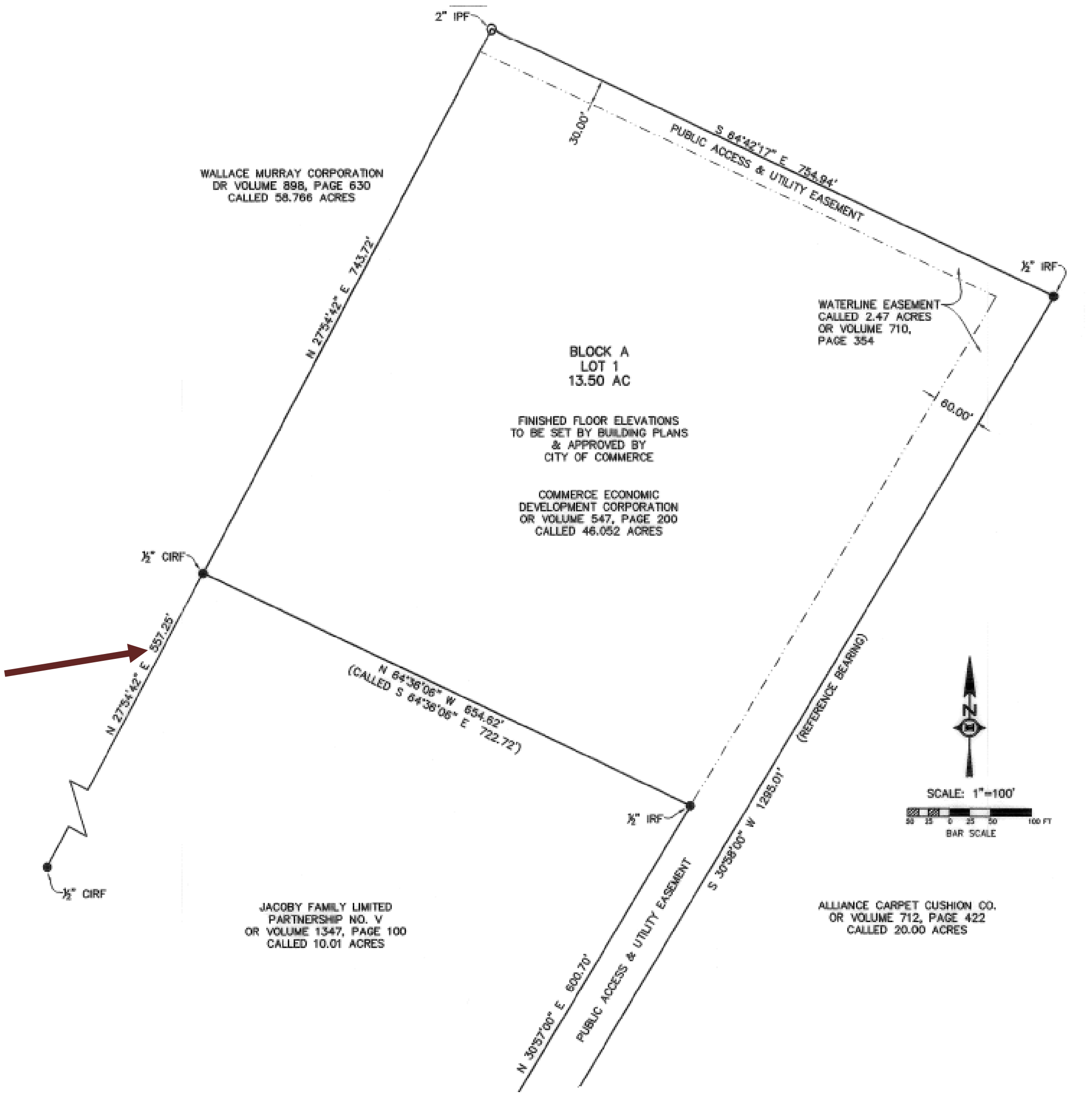

Figure 5 – Connection Lines: The arrow points to an additional measurement that is not part of the boundary being surveyed, but displays an angle and distance measured to a significant point within a metes and bounds system. A surveyor could insert a connection line in the parcel fabric to represent this additional measurement in order to integrate more ground measurements into the system.

2. Parcel points, which store x,y,z coordinates derived from a least-squares adjustment

Although these points are coordinate based, they represent the resulting corners after a least-squares adjustment has been performed. If geometric continuity between control points and survey data is strong, these parcel points represent an upgraded location of the original measured points, and upgrade the accuracy of interpolating unmeasured points.

3. Parcel polygons, defined by parcel lines

These polygons are the representation of the parcel lines after being imported into the coordinate system and assembled as closed shapes. The polygons can store some different measurement information such as misclosure ratio and the rotation and scale at which the parcel was amended to fit into the coordinate network.

4. Line points, which are parcel corner points that lie on the boundaries of adjacent parcels

In the surveying community, line points would be known as calculated points along a known straight line when measured monuments or legal descriptions in a deed sketch do not lie in a straight line (Robillard et al., 2003).

5. Control points, which have accurate, published coordinates for a physical location

The use of control points in a MBGIS was discussed above. In terms of the parcel fabric, control points are always tied to a parcel corner point giving them an absolute location. In terms of a MBGIS surveying environment, control points are accurately located within the system and ordained to be absolute. The term fabric in parcel fabric is indeed a metaphor for the manner in which the points, lines and polygons of the feature class interact with each other. Control points in the parcel fabric are best described as the points at which the fabric is “pinned” down (Esri, 2012) and cannot deviate from that position. All positions between control points can still be molded and adjusted, but control point coordinates are absolute.

6. Plans (table), which store information about the record of survey

The weighting procedure of measured positions is stored in the plans table. Each plan is prescribed an accuracy attribute, the default being categories 1 (highest accuracy) to 7 (lowest accuracy). The different accuracy ratings participate as weighting methods within the least-squares adjustment process of the network. Each parcel and parcel line is drawn or constructed within a plan thus giving that parcel and its lines a certain accuracy weight for the least-squares adjustment. A plan may encompass the survey of a single parcel or of many associated parcels completed in a single survey project.

7. Accuracies (table), which weight parcels in the least-squares adjustment

Known accuracies about each element of the parcel fabric is stored in this table and accessed by the least-squares adjustment of the network. Although the default accuracies were used for this research, they can be customized. Table 1 displays the details of the different accuracy categories that can be assigned to each parcel in the fabric dataset. The least-squares adjustment process uses these survey-style accuracy thresholds when assigning weights to each parcel category. Standard deviation indicates precision, or the spread of values when measuring the same target, whereas part per million (PPM) is a measure of change or uncertainty in measurements and indicates accuracy. The default levels 4 and 5 in the table contain the same PPM threshold but different standard deviations indicating level 4 Accuracy measurements in the default settings contain more precise but not necessarily more accurate measurements than level 5 Accuracy measurements. The Description column shows the time period when this level of accuracy was the best that could be achieved and it is used as one means of assigning an accuracy level if no other information is available.

Table 1 - Parcel Fabric Accuracy Table: This table was taken from the ArcGIS 10.0 Help Desktop Menu and displays the default settings for each accuracy category.
Source: http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//001t00000145000000.htm

Accuracy level	**Std. deviation bearing (secs)**	**Std. deviation distance (m/ft)**	**PPM (m) (parts per million)**	**Description**
1	5	0.001/0.00328	5	Highest
2	30	0.01/0.0328	25	After 1980
3	60	0.02/0.0656	50	1908–1980
4	120	0.05/0.164	125	1881–1907
5	300	0.2/0.656	125	Before 1881
6	3,600	1/3.28	1,000	1800
7	6,000	10/32.8	5,000	Lowest—excluded from adjustment

8. Adjustment vectors (table), which store sets of displacement vectors from least-squares adjustments

The adjustment vectors are an integral part of the parcel fabric and also important within a MBGIS. This table stores the necessary information to adjust feature classes related to the parcel fabric. For example, an access easement can be related to a parcel line as being offset sixty feet and parallel to that line. Therefore, if the parcel line is altered during the least-squares adjustment process, the adjustment vector table stores the necessary information to update the access easement, ensuring data integrity through the measurement-based relationship (Goodchild, 2002).

Figure 6, from Esri's Desktop Help Web page, describes the relationships between the many parts mentioned above that form the parcel fabric data model. Because the fabric retains original measurements, contains methods to adjust error and improve accuracy, and stores a design to interpolate related features as a result of adjusted positions, one may call it a measurement-based system. Figure 6 illustrates all the parts that store measured data (Lines, Control, and Line Points) and the relationships modeled to weight and execute the error adjustment process within the parcel fabric.

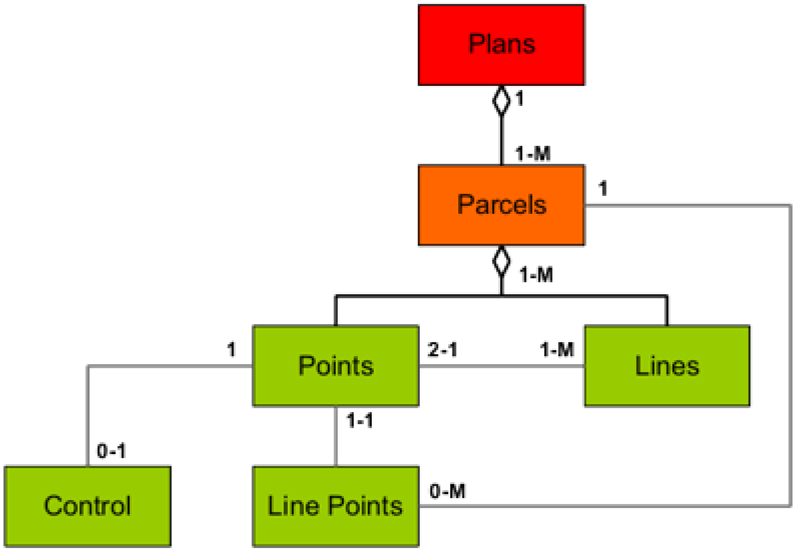

Figure 6 - Parcel Fabric Data Model: This UML diagram from Esri's ArcGIS documentation displays the relationships between the many parts that make up the parcel fabric. Source: http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/The_parcel_data_model_in_the_parcel_fabric/008500000003000000/

4.2 Examples of Measurement Elements

The elements described above create the framework within the parcel fabric that retain original measurements and drive the least-squares adjustment process, both of which must exist to successfully manage metes and bounds survey data within a MBGIS. This section provides practical demonstrations of how survey data is initially integrated into the parcel fabric, how additional survey data is added, and the effect it has on the management of the parcel fabric as a MBGIS.

4.2.1 Integrating Survey Data

A CAD dataset of survey data obtained in Hunt County, Texas, containing a network of several surveyed points shown in Figure 7, was initially input into the parcel fabric. The original data was gathered in the field using an assumed coordinate system where the original point established in space was given an <x, y, z> ground coordinate of <5000, 5000, 100>, respectively.

Because survey data must state the basis of bearing for a particular project, the points in this dataset were rotated to the State Highway shown in the northerly portion of Figure 7. The highway plans were designed and platted using a State Plane bearing reference. This meant that the CAD dataset, although rotated to a different bearing basis than originally collected in the field, still retained relative angles and distances between other measured points collected in the field, but was merely rotated – not scaled into a grid coordinate system – to match the highway plans. This also meant that one could overlay the CAD dataset onto aerial imagery that was rectified using State Plane coordinates consistent with the highway.

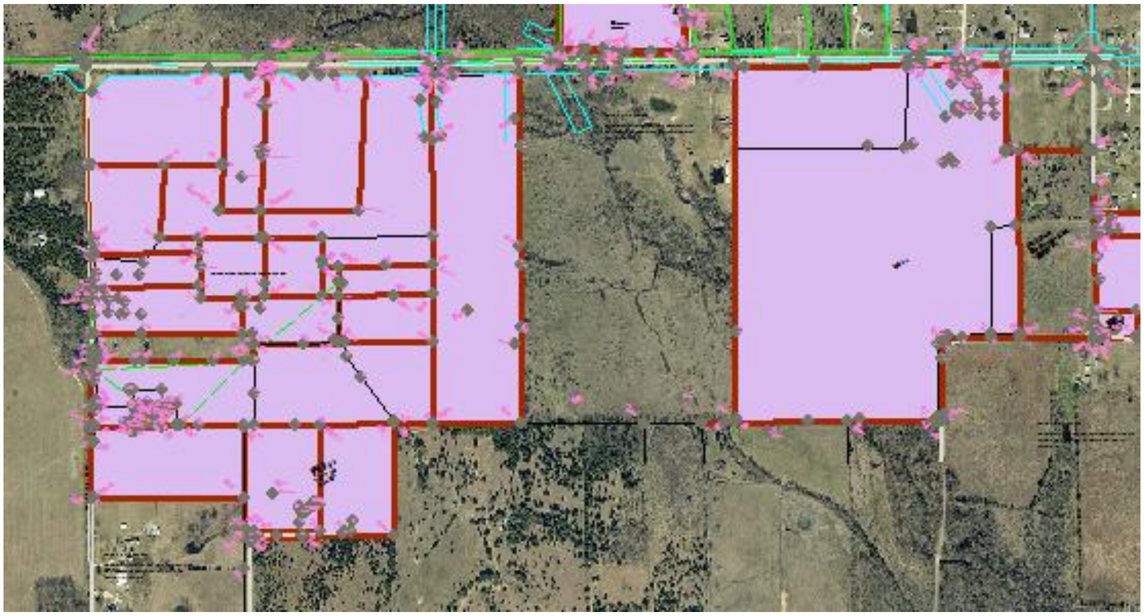

Figure 7 - Initial CAD Import: These are the original lines and points imported into the study area created in a CAD environment. This data was retrieved from Stovall and Associates, Inc., a land surveying and mapping firm in Greenville, Hunt County, Texas. It displays property lines determined by points measured in the field. All red lines in the image are coded to be correct in terms of their measured positions and their relationship to adjoining tracts of land. The red lines were imported into the study area data model and given the highest accuracy rating.

To ensure data was imported correctly and affirm the original measurements were stored in the right fields designated in the Parcel Fabric data model, instructions on how to import a CAD dataset provided in Esri's "Loading Data into a Parcel Fabric" white paper were followed carefully. A requirement of importing the CAD dataset was to declare a coordinate system for the data. State Plane North Central Texas Zone (U.S. Survey Feet) was chosen. The "Load a Topology into a Parcel Fabric" tool was then used to load the line and parcels created from the CAD dataset.

4.2.2 Establishing Control Points

To simulate the collection of GPS points in the field, appropriate control points were created manually so that data would be similar to that produced by a ground survey in the field using GPS. Such control points produce geometric unity for better error adjustment. Several control points were created at the location of different surveyed parcel corners in the system. These became the absolute positional coordinates from which least-squares adjustment was initiated and the fabric was "pinned" to the canvas. Connection lines were also established across a State Highway dividing some of the parcels. Since State right-of-way is considered the senior tract in relationship to adjoining parcels, maintaining right-of-way width is important to producing an accurate system. The connection lines were given the ground-measured width as indicated by the distances displayed on the State right-of-way map. Figure 8 displays the connection lines created across the right-of-way in the study area.

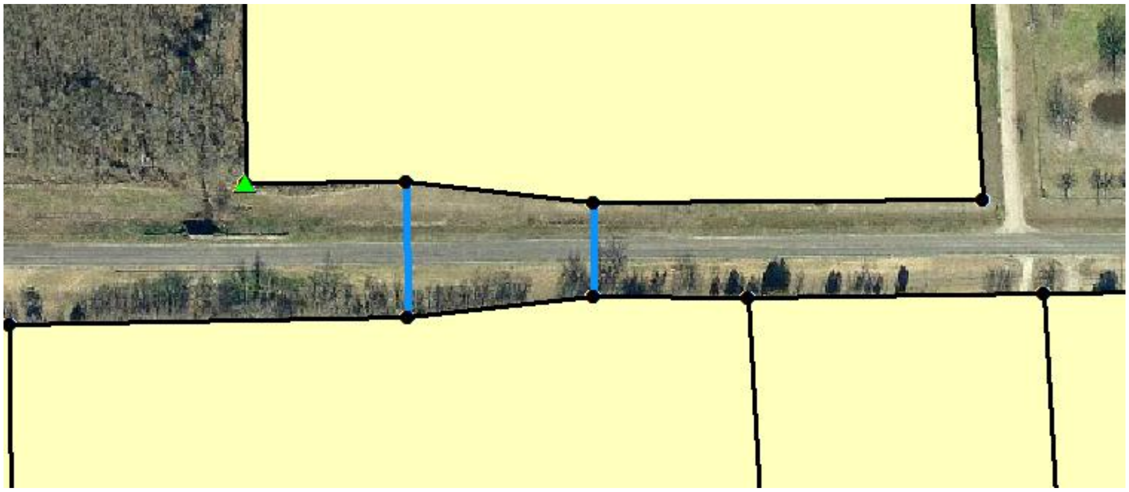

Figure 8 - Connection Lines within the Study Area: The blue lines are connection lines drawn across highway right-of-way that ensure the ground-measured width of the right-of-way during the adjustment process.

An initial least-squares adjustment was compiled to test the continuity of the survey dataset and the control network. Its results proved to be a positive fit of data and resulting coordinate shifts in parcel corner points were minimal. However, the slight coordinate shifts did indicate some error between measured positions that had been adjusted. The error was within survey measurement tolerances, but the shift was still noted. The resulting file of the first least-squares adjustment is presented in the Appendix.

An additional test within the study was undertaken to illustrate coordinate shifts of parcel corner points when they are tied to a control point. The system assumes that a control point has an absolute location of the point in space. This assumption is based upon the method of establishment of control points. As mentioned above, control points *must* be the most accurately established points within the coordinate dataset.

A control point in the system was given a slightly different coordinate than that of its corresponding parcel corner point as shown by the image on the left in Figure 9. Once the least-squares adjustment process was performed on the network, the parcel corner point shifted in line with the control point, since they were intended to be at the same position in space. The image on the right in Figure 9 displays the results of the adjustment.

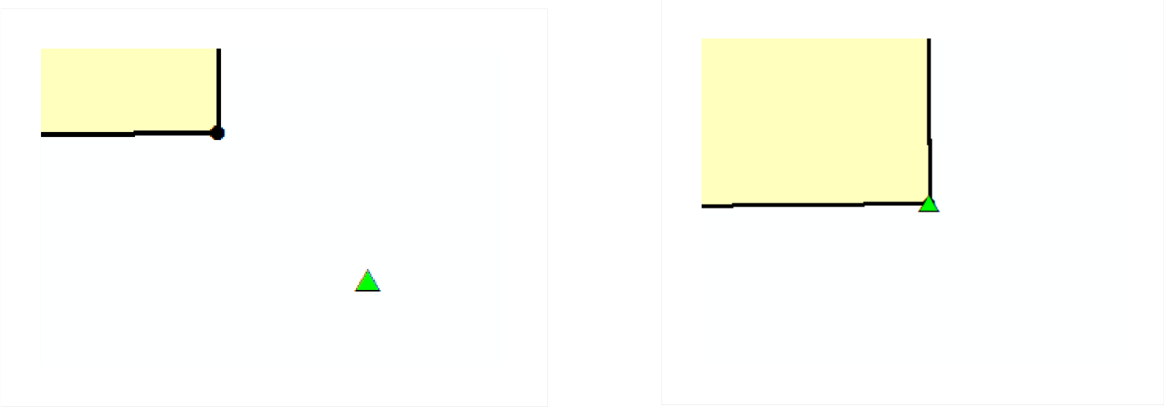

Figure 9 - Parcel Coordinate Shifts: The two images above display the parcel layer and the parcel point that is coincident with a corresponding control point. In the right image the parcel is shifted after a least-squares adjustment. The original coordinates for each point differed slightly before the adjustment and were identical afterward.

This test illustrates the use of control points within a surveying network. When certain property corners are be established using "control point" accuracy, they become absolute positions in space relative to other unmeasured positions. When lines between control points are original tract lines being surveyed, one may see the benefit of "pinning" the endpoints resulting in points along that line being established with greater precision.

4.2.3 Adding Parcels

Parcels can be added to the fabric using several methods. The three most popular methods are:

- Adding CAD data, as was the case for the initial setup of the study area.
- Using coordinate geometry (COGO) tools within the parcel fabric to input a written legal description which is illustrated below.
- Digitization based on aerial imagery or other reference data.

The final method was not used in this study because this research is intended to demonstrate methods in which land surveyors could input metes and bounds data into a MBGIS and retain a reliable system. Parcel digitization would not fall within accuracy thresholds desired by surveyors.

Parcels were added to the network in an attempt to display the use of error adjustment within the network for increased accuracy when interpolating between measured positions. Figure 10 is an image of the study area after the new parcels were added using the parcel fabric COGO tools in accordance to their legal descriptions listed in the most recent deed of the property filed at the Hunt County Courthouse. Three parcels were initially created, according to their legal description, to fill a large hole in the original fabric. They were given a different weight from that of the original parcels in the fabric, using only the estimated date of the legal description as a factor (the default setting in the parcel fabric).

When a parcel is added to the fabric, its initial starting point is assumed to be in a local coordinate system and given a northing and easting of <0,0>. The ground dimensions are used to input internal angles of the property and a Bowditch adjustment[3] is used to calculate and correct any misclosure between the start and end point of the traverse. At this time, the parcel is considered unjoined to the fabric and is represented in its raw measurement form.

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[3] The Bowditch rule, also known as the compass rule, is a simple adjustment method that amends angular error by proportionately distributing blunders based upon the length of lines or courses in a traverse versus the overall perimeter of the traverse (Mikhail & Gracie, 1981).

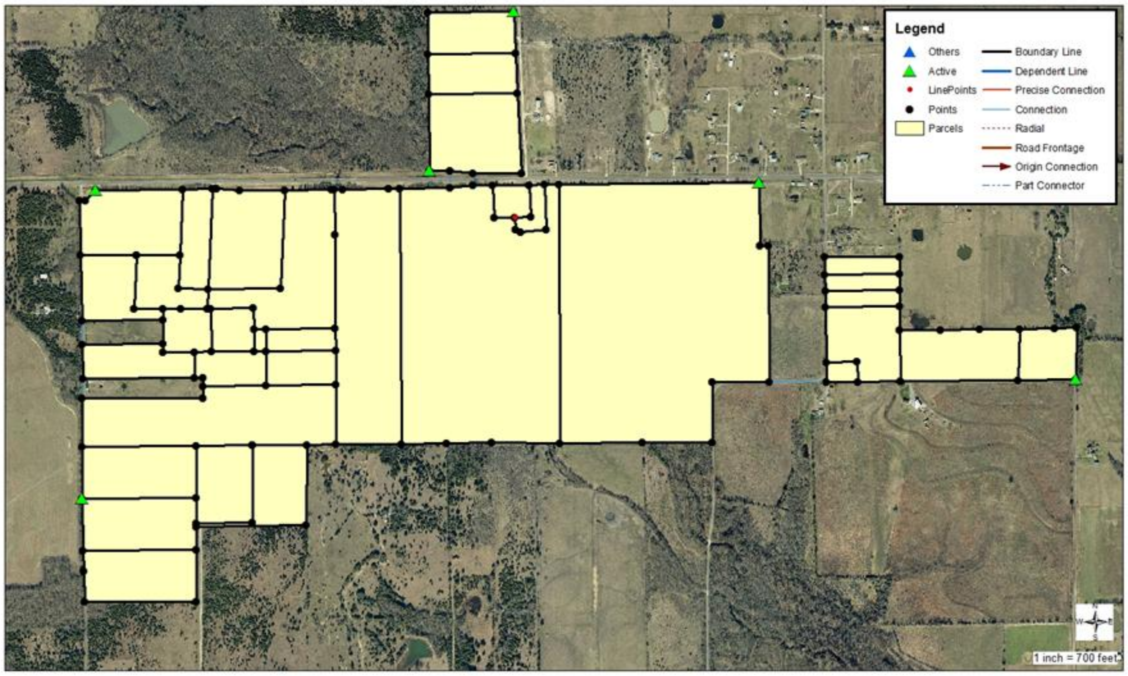

Figure 10 - Adding Parcels: The three parcels were added to the middle of the study area using COGO tools provided within the parcel fabric toolset. A least-squares adjustment was once again performed on the entire study area with favorable results.

The unjoined parcel is then linked to parcels in the fabric through shared points. A Helmert transformation[4] is used (rotation, scale, shift in x, shift in y) to determine the location and representation of the parcel in the fabric. A local least-sqaures adjustment is performed when the user defines more than two links when joining a parcel to the fabric. The Helmert parameters at which the joined parcel fits is stored within the parcel polygon attributes and is used in the bearing equation of the least-squares adjustment.

Once again a least-squares adjustment was performed on the data using the same control points initially established. The result was an additional coordinate shift, but still

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[4] The Helmert transformation is a seven parameter transformation that preserves shape, while adjusting scale, rotation of x, y, and z, and position of x, y, and z, when translating coordinates between two Euclidean spaces (Esri, 2012).

within the default constraints of the test. These three parcels integrated into the network with little resistance and little coordinate shift, suggesting a decent fit of data. The results of the least-squares adjustment can be seen in the Appendix.

4.2.4 Failed Adjustment

Two additional parcels were added to the fabric using the same COGO method as was used for the three above. These two parcels were connected to the study area, but altered the geometric unity of the test site. Figure 11 displays the elongated shapes of the new parcels along the southern edge. Once again a least-squares adjustment was performed on the entire study area; however, the adjustment failed. The failure was due to several parcel lines exceeding the computed-minus-observed (c-o) distance threshold.

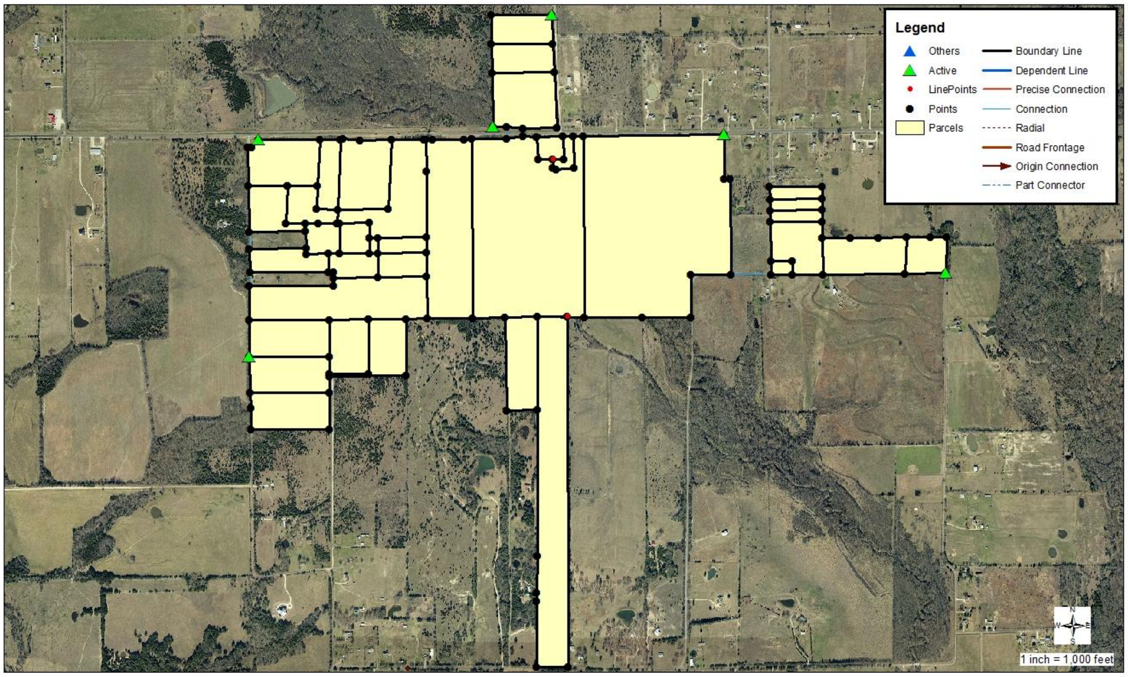

Figure 11 Failed Adjustment: The two odd-shaped parcels added at the bottom of the study area caused several parcel lines to exceed the computed-minus-observed distance tolerance for adjustment, which in turn caused the least-squares adjustment to fail.

The ‘c-o’ computation is the difference between the newly computed coordinate parcel line and the original ground distance or bearing attributes of the line.

There are two possible reasons for failure. The first is the lack of ‘geometric unity’ within the system. As different shaped parcels are integrated into the fabric, translation, rotation and scaling of each new parcel becomes difficult without additonal measured positions on adjacent parcels. More redundancy with lines and points adjacent to the odd-shaped parcel could have resulted in a successful adjustment.

The second reason for failure deals with the issue of ‘bearing basis’ in metes and bounds surveying. As stated, surveyors establish their own compass bearing in a metes and bounds system (Robillard et al., 2006). At times some legal descriptions are far from true north orientation as the parcels are situated in fabric. When this occurs, the ‘c-o’ bearing threshold could cause the adjustment to fail. This failure occurs frequently in a metes and bounds system, where every legal description in an area could have a different ‘bearing basis.’

A possible method to correcting failure due to multiple ‘bearing bases’ is to sketch the original metes and bounds description in another layer using coordinate geometry (COGO) tools. This newly drawn tract of land can then be translated and rotated where it seems to fit in the fabric better. This approach orients the original bearings closer to the fabric rotation. The original bearing is not as critical as retaining original relative angle and distance in metes and bounds as mentioned above because the surveyed line is the line between the two monumented corners at the surveyor’s defined bearing (Robillard et al., 2003). The new rotated bearings can then be used to input the new parcel into the fabric possibly resulting in a successful adjustment of the entire area.

4.2.5 Additional Test

If more time had been available to complete this study, field work would have been performed to locate (with survey-grade accuracy) the property corners of the three legal descriptions input into the system in relationship to the location of the published control points in the system. Then the resulting error between the field measured location and the interpolated position in the parcel fabric would be an indicator of how well the least-squares adjustment was able to correct error in the network and estimate unknown positions with greater accuracy based on the measurements already present in the system. Furthermore, if the new surveyed positions were then added to the network, and additional parcels were added per their legal descriptions, one could test to see if the interpolated positions of these parcels contained less error than the first set, as the theory of a MBGIS indicates they should.

Chapter 5: Towards the Management of Metes and Bounds Data in the Parcel Fabric

The Esri parcel fabric data model is associated with several tools and attributes for storing and utilizing original ground measurements (Esri, 2011). These are the measurements used by land surveyors to solve property boundaries and determine property corners. Because such a system retains and uses original measurements to calculate error between measurements and to determine interpolated positions, one could call it a MBGIS. However, as illustrated in the previous section, there must be certain methodologies practiced in order for one to successfully integrate and manage metes and bounds data with the parcel fabric. This section uses the results of the demonstrations of integrating survey data described above to formulate a protocol to successfully manage metes and bounds survey data using the parcel fabric.

The goal of the surveyor working in the parcel fabric would be to create a seamless network of all his measured points within a service area (city, county, region, etc.). The surveyor's field measured data would be input with the highest accuracy rating in the fabric, as it was all gathered, verified and linked through field measurements and attributes about the measurements are known. Therefore it is the most reliable data within the system.

Other parcels within the network might be given lesser accuracy ratings depending upon the surveyor's assessment of their accuracy. Although the survey date is the default constraint within the accuracy table, other considerations are possible. For example, as noted earlier, more or less weight might be placed on work performed by a particular surveyor in the area because of personal knowledge of that surveyor's work quality.

Thus, even though a surveyor's legal description and survey was performed within the accuracy-level two rating based on time frame, for example, it might be downgraded to accuracy-level three or four.

The goal of the network from a surveying perspective is to interpolate unmeasured property corners as precisely as possible before field crews begin their work on a property. Land surveyors must always attempt to verify property corners in the field (Robillard et al., 2003), a practice that will never be eliminated from surveying. But giving field crews smaller zones in which to look for and identify monuments as property corners can help save time in the field. These monuments can then be measured and their subsequent parcels can then be upgraded to the highest accuracy parcel rating within the fabric.

Control points within a metes and bounds system are irregular in contrast to the systematic nature of the PLSS (Zimmer & Kirkpatrick, 2009). Control points would have to be created by the private surveyor and be well positioned in terms of geometric proportionality. It is evident through the demonstrations above that least-squares adjustments have bearing and distance thresholds in terms of their benefit on the system as a whole. It is more difficult to perform and analyze reliable adjustments to larger areas of metes and bounds tracts. Since control points are "pinned" positions within a system, one could systematically establish these points to regionalize a service area into several different adjustment zones. Neighboring adjustment zones would share common control points for their own adjustment of parcels within their region. The user would still integrate all of their data into one network, but only employ certain control points in user-defined regions for adjustment purposes. Figure 12 illustrates the argument. The parcel fabric is “pinned” at each control point with adjoining regions sharing common points to link the regions together.

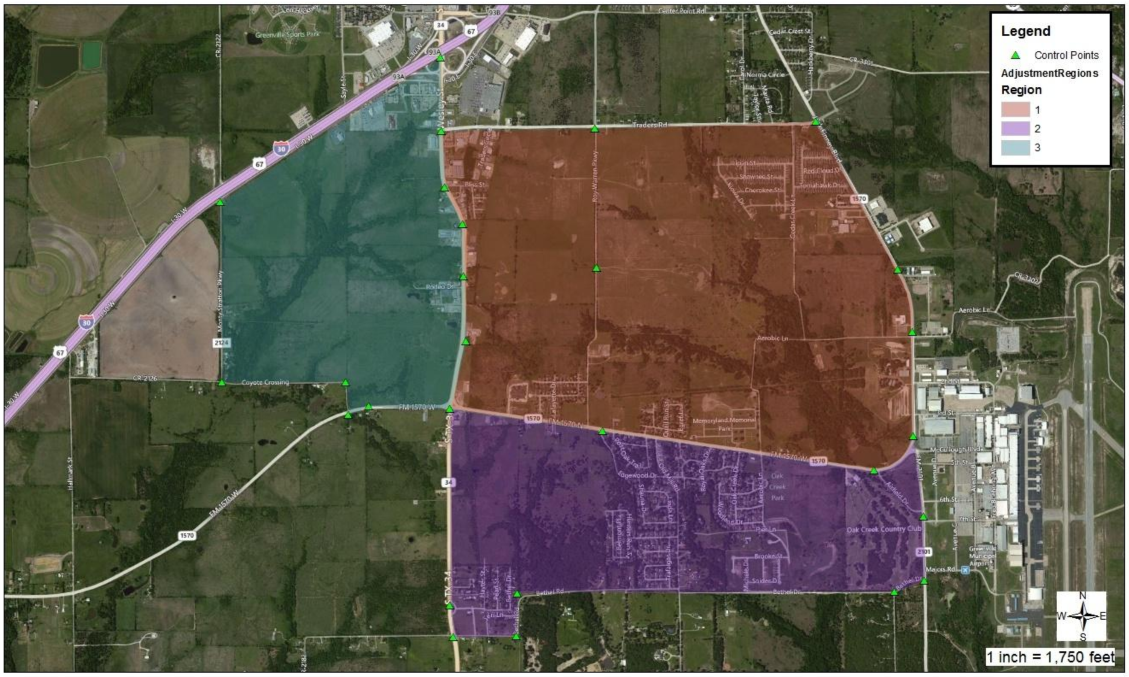

Figure 12 - Control Network Setup: The use of adjustment regions to localize processes is a method to set up control networks for metes and bounds data. Control points could be easily established in street right-of-ways and other public areas to create natural geometric boundaries to ensure accurate least-squares adjustments within localized areas.

Two methods for the geometric placement of control points are seen as best practice within a metes and bounds system. The first involves the surveyor placing control points within street right-of-ways where they would not be trespassing onto private property to access or re-establish the control monument. A road map could be used to plan certain adjustment regions. Figure 12 above illustrates this method.

The second method involves researching older parent tracts as adjustment regions. Once the outer bounds or property corners of parent tracts were established, every child parcel inside the original parent tract would be adjusted relative to the absolute position of the parent tract. This second method, illustrated in Figure 13, could produce a true surveying network of control and adjustment regions based upon the fundamental design of a metes and bounds system, where smaller child tracts are formed relative to their position of larger parent tracts.

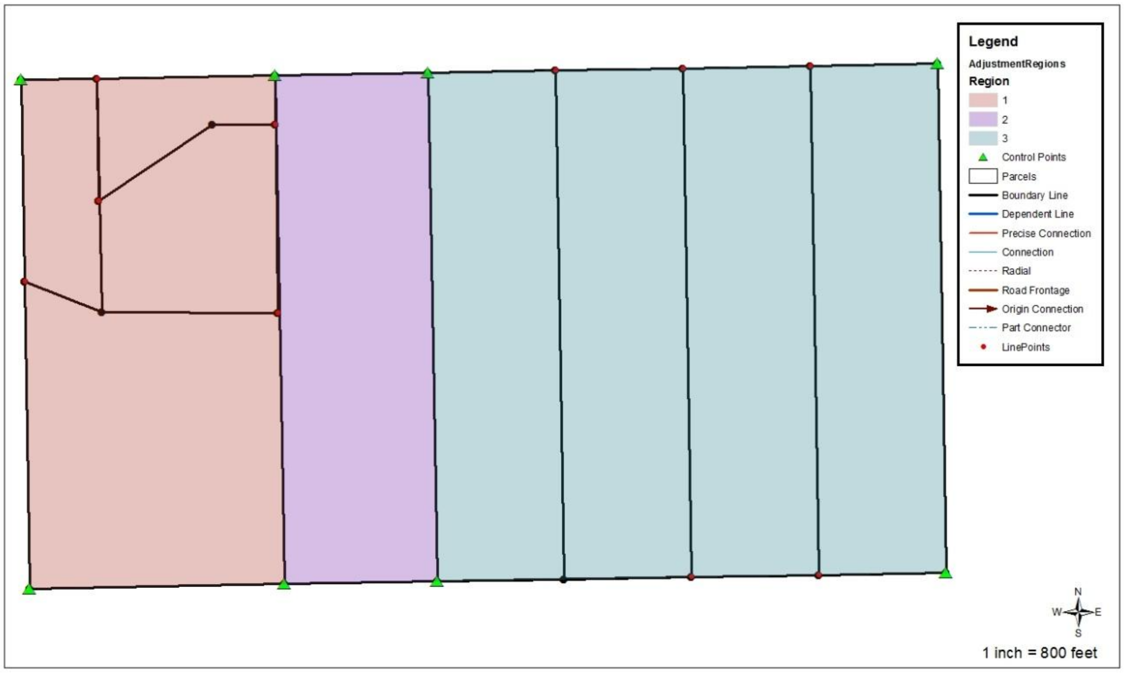

Figure 13 - Parent Tract Adjustment Regions: This image displays three separate parent tracts researched by the surveyor in order to determine least-squares adjustment regions within the parcel fabric. Historical information about parent tracts located in other layers within the MBGIS would match the control network adjustment regions.

For the second method, historical research data, including parcel seniority rights, could be stored in the GIS for later use. This approach would take significant planning and time to establish, however. A survey company could begin with just one adjustment region and slowly add additional regions, and/or integrate regions that are distant from each other. Thus Control networks established using GPS would obviously be preferable as integrating datasets would be of high accuracy-level.

Most elements of metes and bounds survey data can be accurately represented within the parcel fabric. Original CAD data can be integrated into the fabric with the ground measurements retained. The parcels can be assigned weights to justify their existence within the parcel fabric. Control networks can be planned and established using either natural boundaries for adjustment regions or historical tracts can be researched to establish original parent tract adjustment regions. Knowledge of these elements are important for surveyors to gain confidence in the use of the parcel fabric both as a MBGIS and as a “best practice” method to manage survey data.

One final element to consider when adapting metes and bounds survey data to the parcel fabric involves integrating or adding measured points into the fabric. Adding measured positions from GPS would be the simplest method: these could be easily integrated into the system and tied to a specified adjustment region. However, there are times when the capabilities of the GPS are not available to complete ground measurements and traditional surveying instruments must be used. Then, the surveyor must tie into several control points or several common points already established in the fabric. Tieing back to prior surveys not only allows additional redundancy for measurement adjustment operations, but also ensures that new points are integrated into the existing system accurately.

All positions collected in the field (either by GPS or by traditional surveying equipment) would then be linked together in their specified adjustment region and given the highest accuracy as all attributes about the points are known. Adjoining or un-surveyed parcels could then be added per their legal descriptions and given an accuracy rating as mentioned above. The fit of the data and results of adjustment operations would indicate to the user the reliability of un-surveyed tracts of land. Ultimately, more points gathered in the field would result in high accuracy survey regions and precise estimations for interpolated positions. Correctly estimating interpolated positions could save tremendous time in the field.

Chapter 6: Discussion

The parcel fabric data model contains several features that are indicative of a measurement-based system. The lines within the model store original ground measurements which are used in a least-squares adjustment process, where resulting vector tables can be used to incrementally correct other features within the data model. Resulting parcel corner point locations indicate a more accurate interpretation of how properties are represented on the ground. However, there are several elements of the parcel fabric that do not fit within the theory of a MBGIS. These elements are mentioned below.

The irony of the parcel data model and using the parcel fabric is the first thing a user must do is define a coordinate system (Esri, 2011). One could argue that ground measurements are already compromised by this initial system definition and it is impossible to correct or update parts of the system without creating geometric distortion (Goodchild, 2002). This problem is evident within the least-squares adjustments on the sample data and fabric adjustments demonstrated above. As more parcels were created based upon their recorded legal descriptions, it became difficult to successfully complete an adjustment in relation to the absolute coordinate location of control points within the default thresholds of the adjustment process. The problem arises from the many different bearing bases and distance factors used by land surveyors who have performed work in a given area. These cannot all be adjusted relative to absolute positions while maintaining the accuracy thresholds displayed in Table 1 above. Because of the unknowns within the metes and bounds systems, the least-squares adjustment fails or topological distortions are created if the adjustment tool thresholds are expanded. Therefore adjustments would have to be constrained to very localized regions to ensure geometric unity.

A second survey-related issue arises from the use of a projected coordinate system for the parcel fabric to represent tracts of land in space. The original theory of MBGIS (Goodchild, 2002) as it relates to representing land surveying data describes a system where all linked measurements contain the same spatial reference or the functions needed to derive a common spatial reference and are scaled to ground measurements. Additional measurements are then incrementally added to the system using the same survey parameters (ground rotation and scale) thus allowing the original measurements to carry the information needed to correct uncertainty (Buyong et al., 1991). This simplicity is not possible within the parcel fabric feature class. Parcel lines store original ground measurements which are used for adjustment purposes, but parcels are only linked through the projected coordinates of parcel corner points.

There is also no method within the parcel fabric of calculating errors of original measurements based on the addition of ground measurements to the network. This type of calculation would give the user the ability to determine uncertainty in particular measurements within the system (Goodchild, 2002). The only method of doing this in the current parcel fabric involves the “guessing game” of a user-assigned accuracy level. Instead the user must define the geometric boundaries and control network in which he believes the least-squares adjustments will not fail or create topological distortions.

The parcel fabric also does not allow the transformation of parcel corner points back to original ground measurements once they are in a projected coordinate system.

Some argue the optimal method of representing data is within a projected coordinate system for data visualization and representation purposes (Jackson & Rambeau Sr., 2007). However, a land surveyor must have the ability to use the coordinates derived in the system on the ground to set new property corners and other monuments and to link additional measurements. Since projections ultimately distort the geometry of the earth's surface, the use of displayed parcel corner coordinates would arguably be incorrect if used to establish ground points.

Chapter 7: Conclusion

The goal of this research was to investigate and explore the management of metes and bounds survey data integrated into a GIS. Traditional GIS practices and coordinate-based systems are not ideal for the storage and retrieval of measurement-based survey data. Rather if metes and bounds data is to be managed in a GIS environment, then the system *must* be a MBGIS.

The retention and use of original measurements within a MBGIS for metes and bounds survey data was theorized in Section 3 and relationships that must exist between measured points were established. This proved that MBGIS provides a suitable format to manage traditional metes and bounds survey data as well as modern data collected from popular technologies such as GPS. A MBGIS for survey data would contain the capabilities to:

- Retain these original survey measurements to reuse in the field and to link to additional points.
- Apply metes and bounds surveying rules to determine a property boundary.
- Assess unprojected error within the system for quality assurance purposes.

Skepticism of GIS within the surrveying community is a result of the traditional practices of GIS (Deakin, 2008). Using a MBGIS to manage metes and bounds survey data would produce less skepticism among surveyors. Esri’s ArcGIS 10 parcel fabric data model was proposed as a “best practice” to manage metes and bounds survey data within a GIS because it contains elements of a measurement-based system.

Section 4 illustrated several elements of the parcel fabric that incorporate original ground measurements. To explore and test the measurement-based elements of the parcel fabric, a CAD dataset was integrated into an empty parcel fabric model, then parcels were added to the fabric and least-squares adjustments were applied. It was discovered that original measurements stored within the fabric play a large role in the adjustment process as well as accuracy weighting within the network.

These demonstrations indicate that the parcel fabric is suitable to manage metes and bounds survey data. However, the surveyor creating the system would need to plan adjustment zones appropriately in order for the parcel fabric to best utilize original measurements. The surveyor would ultimately designate his own ground measurements as the highest accuracy weight, while assigning different accuracy weights to other data added to the fabric. Adjustments would then be more reliant upon ground measurements taken by the surveyor and the geometry of the adjustment zones.

Managing survey data within a GIS environment would be beneficial to both the GIS and surveying communities. Surveyors would obtain an ability to manage their data in one system, while the GIS community would obtain the benefit of highly accurate data managed by others. If the surveying community is to become less apprehensive to use GIS to manage their data—especially when managing data in metes and bounds states like Texas—knowledge of how measured positions are retained and utilized within a GIS is necessary.

Esri’s parcel fabric does indeed contain most aspects of a measurement-based system, and has the capabilities to manage metes and bounds survey data. However, future work must be done to eliminate the drawbacks of the fabric model discovered in this study, in particular: retaining measurements, applying survey rules, and assessing unprojected error. For surveyors, having a MBGIS where error between original measurements can be assessed and where groups of fitted coordinates can be transformed back to their measurable locations on the ground is essential. The additions outlined here would establish Esri’s parcel fabric as a MBGIS suitable for surveyors, even in metes and bounds states such as Texas. This, in turn, would allow surveyors to integrate GIS successfully into their business processes, providing tools to manage and retain their original measurements on a long-term basis.

Glossary

Azimuth: Unit of angular measurement between two points determined by the number of degrees from north measured from 0 to 359 rotating in a clockwise direction. North in azimuth angle measurements can be magnetic or true north, or designated by the surveyor.

Bearing: The horizontal angle that a line makes with the meridian of reference adjacent to the quadrant in which the line lies. Bearings are classified according to the meridian of reference, as: astronomic, geodetic, magnetic, grid, assumed, etc. A bearing is identified by naming the end of the meridian from which it is reckoned, either north or south, and the direction of that reckoning, either east or west. Thus, a line in the northeast quadrant making an angle of 50 degrees from the reference meridian will have a bearing of N 50 degrees E.

Bearing Basis (Rotation, Control Line): The bearing between two points on a survey which serves as the reference system for all other lines on the survey.

Call: Any single monument, landmark or measurement mentioned in a legal description. For example, North 90 degrees east, 350 feet is a call, or East 6000 feet to a concrete monument. A series of calls which begin and end in the same position form the legal description of a property.

Child Tract: A tract of land (smaller than parent tracts) that were split from larger parent tracts and sold.

Control Point: A point in space determined to be located with the greatest precision and accuracy. Most control points in modern surveying are determined using RTK or differentially corrected GPS technology.

Coordinate: A set of numbers (x, y, z) used in specifying the location of a point.

Coordinate Geometry: Also known as COGO, is an automated process to sketch legal descriptions and other surveys using the angles, distances and monuments provided by surveyors in their property descriptions.

Data Collector: A device used in the field while surveying that records and stores angles and distances between objects located in the field that are pertinent to completing a boundary survey.

Distance: The unit of measure, most commonly described in Texas in units of feet, used in surveying to help describe the relationship between two points. In terms of land surveying, distance is synonymous with slope distance, which is the calculated distance between two points at different elevations. More traditional distance units of surveying in Texas include the chain, link, Spanish vara, yard, and rod.

Evidence: Physical objects, monuments, traces of objects or any other object or relationship discovered and measured in the field while performing a survey that aids in correctly determining the metes and bounds of a parcel of land.

Ground Measurement: The actual measurement determined using surveying instrumentation in the field where no scale factor or projection has been applied to the measurement itself.

Junior Tract: The youngest of two or more adjacent survey whose angles, distances, and monument calls are subordinate to tracts of land that are senior. Junior tracts are usually the last child tracts split from a parent tract of land.

Metes and Bounds: A method of surveying in which a property is described by angles, distances, and monuments on the ground (metes) in relationship to adjacent tracts (bounds).

Monument: A permanently placed marking on the surface of or in the ground that is used to represent a property corner of a parcel of land or some other important feature such as a control point. These include iron re-bar sunken into the ground, concrete monuments, a chiseled X or V in concrete, or a nail hammered into asphalt.

Parent Tract: A tract of land (usually quite large at one point in time) from which additional ‘child tracts’ are split.

Raw Data: The original angles, distances, and descriptions of objects found in the field while surveying, usually stored in a data collector in the field and downloaded to a computer at the office. Raw data is used in most surveying software for error analysis and adjustment.

Real Time Kinematic (RTK): A method of satellite navigation technology used in land surveying where a single reference station (also known as a base station) provides real-time corrections to a rover collecting positions, providing sub-centimeter accuracy without post-processing.

Right-of-Way: The strip of land that determines the legal width of a road or railroad or the width of a pipeline, power line, or telephone easement.

Scale Factor: The factor by which a set of measurements are multiplied to transform the measurements into a projected plane or coordinate system.

Senior Tract: The eldest of two or more adjacent surveys whose angles, distances, and monument calls take precedence over junior tracts. The most senior tract is usually the first child tract split from a parent tract of land.

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Appendix: Least-Squares Adjustment Results

The data below are the results of the three least-squares adjustments generated by ArcGIS in a temporary text file. The data in the text file was copied and pasted to this appendix. They show whether the adjustment was completed or if it failed. The first set of results is from the initial least-squares adjustment. The second set shows the results after three parcels were added, and the third set is from the failed adjustment. Each set contains different error residuals and additional statistics about the adjustment process that indicate to the user if how the parcels were adjusted in space.

Initial Least-squares Adjustment

```
Craig Bartosh: USC Spatial Sciences          Adjustment of Parcels                Page: 1
Parcel Editor
  ADJUSTMENT COMPLETED

Adjustment Settings
======================
Linear Units   : Foot_US
Coordinate System: NAD_1983_StatePlane_Texas_North_Central_FIPS_4202_Feet
         No height data, assuming parcels are at sea level
Check Tolerances:
        Bearings     1°40'00"
        Distances 0.33
Dependent lines   : No
Historical Data : Yes
Fixed Boundary   : No
Results File    : C:\Users\CBARTO~1\AppData\Local\Temp\FabricAdjustmentReport.lst

Adjustment Statistical Summary
=============================
Number of Control Points     =      9
Number of Parcels            =     31
Number of Points             =     77
Number of Bearings           =    170
Number of Distances          =    170
Number of Unknowns           =    167
Redundancy                   =    173
Bearings Exceeding Tolerance   =      0
Distances Exceeding Tolerance  =      4
Close Points Found           =      0
Line Point Errors Found      =      0
```

```
Max. coordinate shift: Easting =   -0.000,  Northing =    0.000 at point 119
Average coordinate shift: Easting =   -0.000,  Northing=  -0.000
Mean(average) of coordinate residuals      =    0.01
Standard deviation of coordinate residuals =    0.05
Range of coordinate residuals           =    0.22


Close Points Report: Tolerance = 0.656
===================
0 close points found.

Linepoints Report: Tolerance = 0.656
===================
0 Linepoints found outside of the Check Tolerance

Parcel Lines Report - Difference between Computed and Observed/Recorded (c-o)
============
   1/ModernSurveys Line: 68-71  Distance(c-o)=0.365
   TAParcels_483/<map> Line: 64-68  Distance(c-o)=0.548
   TAParcels_483/<map> Line: 68-71  Distance(c-o)=0.365
   TAParcels_483/<map> Line: 71-70  Distance(c-o)=0.334

Suspect Points and Lines (exceeds 3x std deviation of adjusted data)
========================
Plan/Parcel       Parcel Misclose    Point     dx       dy
<map>/TAParcels_483      0.000     0.001       64     0.056     0.016

Plan/Parcel       Parcel misclose    From    To    Length    (c-o)
StovallSurvey/TAParcels_479       -0.001      0.000       53       52    665.970     0.085
<map>/TAParcels_483       0.000      0.001       64       72    150.061     0.105
<map>/TAParcels_483       0.000      0.001       68       71    675.353     0.111
<map>/TAParcels_483       0.000      0.001       71       70    523.083     0.102
ModernSurveys/1       0.000      0.000       52       68    413.388     0.053
ModernSurveys/1       0.000      0.000       68       71    675.353     0.111
ModernSurveys/1       0.000      0.000       53       52    665.970     0.085
DigitizedParcels/NewParcel37       0.000      0.000      115      116    194.982     0.054



---------- Control Report ----------
            TRANSFORMATION RESULTS
 Point     X            Y          dx       dy        Name
#  99  2687639.598 7071752.786     0.000     0.000   CP_99
#   6  2684056.023 7070223.857     0.000     0.000   CP_6
#  57  2683941.106 7067581.659     0.000     0.000   CP_57
#  89  2692458.541 7068600.426     0.000     0.000   CP_89
#  68  2688033.370 7068056.512     0.000     0.000   CP_68
#  70  2689743.861 7070288.805     0.000     0.000   CP_70
#  53  2686664.716 7070234.055     0.000     0.000   CP_53
#  52  2686677.131 7068049.154     0.000     0.000   CP_52
```

Least-Squares with three new Parcels

```
Craig Bartosh: USC Spatial Sciences        Adjustment of Parcels              Page: 1
Parcel Editor     ADJUSTMENT COMPLETED

Adjustment Settings
======================
Linear Units   : Foot_US
Coordinate System: NAD_1983_StatePlane_Texas_North_Central_FIPS_4202_Feet
Check Tolerances:
      Bearings     1°40'00"
      Distances 0.33
Dependent lines   : No
Historical Data : Yes
Fixed Boundary   : No
Results File    : C:\Users\CBARTO~1\AppData\Local\Temp\FabricAdjustmentReport.lst

Adjustment Statistical Summary
=============================
Number of Control Points      =       6
Number of Parcels             =      34
Number of Points              =      91
Number of Bearings            =     200
Number of Distances           =     198
Number of Unknowns            =     205
Redundancy                    =     193
Bearings Exceeding Tolerance   =       0
Distances Exceeding Tolerance  =       3
Close Points Found            =       0
Line Point Errors Found       =       0

Max. coordinate shift: Easting =    0.665,  Northing =   -0.495 at point 182
Average coordinate shift: Easting =   -0.020,  Northing=  -0.014
Mean(average) of coordinate residuals      =    0.01
Standard deviation of coordinate residuals =    0.16
Range of coordinate residuals          =    0.78

Warning: Control point CP_53 references no point ID
Warning: Control point CP_52 references no point ID
Warning: Control point CP_68 references no point ID

Close Points Report: Tolerance = 0.656
===================
0 close points found.

Linepoints Report: Tolerance = 0.656
===================
0 Linepoints found outside of the Check Tolerance

Parcel Lines Report - Difference between Computed and Observed/Recorded (c-o)
============
  1/ModernSurveys Line: 183-184  Distance(c-o)=0.776
```

```
   1/OldSurveys Line: 129-128  Distance(c-o)=-0.490
   1/OldSurveys Line: 128-129  Distance(c-o)=-0.490

Suspect Points and Lines (exceeds 3x std deviation of adjusted data)
========================
Plan/Parcel      Parcel Misclose    Point     dx       dy
OldSurveys/1     0.000    -0.000     183     0.100    -0.130
OldSurveys/1     0.000    -0.000     182     0.143    -0.121
OldSurveys/1     0.000    -0.000     181     0.151    -0.101
OldSurveys/1     0.000    -0.000      68     0.133     0.089
OldSurveys/1     0.000    -0.000      52    -0.145     0.061
OldSurveys/1     0.000    -0.000      53    -0.144    -0.055

Plan/Parcel      Parcel misclose    From    To    Length    (c-o)
OldSurveys/1       0.000     -0.000      186      183     53.329     0.229
OldSurveys/1       0.000     -0.000      128      129    117.013     0.164

 Error vectors between Inactive Control Points and Fabric points
========================================
Point   Bearing  Distance  Name
     0  N00°48'23E 7563489.730  CP_53
     0  N00°48'45E 7561451.769  CP_52
     0  N00°49'19E 7561940.641  CP_68



---------- Control Report ----------
             TRANSFORMATION RESULTS
 Point     X           Y          dx       dy        Name
#  99  2687639.598 7071752.786     0.000     0.000   CP_99
#   6  2684056.023 7070223.857     0.000    -0.000   CP_6
#  57  2683941.106 7067581.659    -0.000     0.000   CP_57
#  89  2692458.541 7068600.426     0.000    -0.000   CP_89
#  70  2689743.861 7070288.805    -0.000     0.000   CP_70
#  90  2686918.470 7070386.530    -0.000    -0.000   CP_90
```

Failed Results

```
Craig Bartosh: USC Spatial Sciences            Adjustment of Parcels                    Page: 1
Parcel Editor     ADJUSTMENT FAILED

Close Points Report: Tolerance = 0.656
===================
0 close points found.

Linepoints Report: Tolerance = 0.656
===================
1/OldSurveys Line: 208-68 Linepoint=225, Offset=  5.638
1 Linepoints found outside of the Check Tolerance

Parcel Lines Report - Difference between Computed and Observed/Recorded (c-o)
============
   TAParcels_489/StovallSurvey Line: 94-92  Distance(c-o)=0.456
## TAParcels_483/<map> Line: 64-68  Distance(c-o)=1.091
   TAParcels_483/<map> Line: 71-70  Distance(c-o)=0.562
   1/ModernSurveys Line: 194-195  Distance(c-o)=0.859
   1/ModernSurveys Line: 196-190  Distance(c-o)=-0.429
## 1/ModernSurveys Line: 209-208  Distance(c-o)=8.297
   1/ModernSurveys Line: 208-212  Distance(c-o)=-0.846
## 1/ModernSurveys Line: 212-209  Distance(c-o)=-5.563
   1/OldSurveys Line: 198-196  Distance(c-o)=0.480
## 1/OldSurveys Line: 68-208  Distance(c-o)=-8.485
## 1/OldSurveys Line: 208-209  Distance(c-o)=8.836
   1/OldSurveys Line: 225-68  Bearing(c-o)=    2°27'19", Effect=8.617
ERROR: Unable to complete adjustment. 5 parcel lines did not adjust within 3x the specified tolerances.
```