Computer Assisted Post Election Audits*
(Extended Abstract)

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Abstract

The introduction of electronic voting technology in Connecticut necessitated the development of new policies and procedures by the Secretary of the State (SOTS) Office to safeguard the integrity and security of the new electoral process. Forming a partnership with the University of Connecticut, SOTS Office developed a comprehensive approach that extended the existing electoral procedures to incorporate the use of the new optical scan electronic voting equipment. The new procedures include pre- and post- election audits of the voting equipment programming, and hand-counted post-election audits in 10% of randomly selected districts. Observing that the hand-counted audits are expensive, time-consuming, labor-intensive, and error-pone, it was decided to explore a semi-automated approach to post-election ballot audits. A semi-automated approach was chosen over a completely automated one due to the risks and inadequacy of the latter. Supported by the U.S. EAC and the State of Connecticut, an Audit Station was developed for the purpose of conducting computer-assisted post-election audits. The Audit Station speeds up the audit process, increases audit accuracy, and most importantly, empowers the human auditors to have complete control over the audit down to the interpretation of each voted “bubble.” In essence, the Audit Station does not take the place of a hand count, but augments it by presenting scanned ballot images with useful data for the auditors to consider or to contrast with the official paper ballots. The system is also auditable; upon the completion of the audit it exports the recorded ballot interpretations and the overall results that allow direct comparison with physical ballots and independent validation. The system is implemented using inexpensive commercial off-the-self components, and is equipped with a projector that enables the auditors (and the public) to easily observe the audit process and to control and override it as necessary. The system was recently used in successful pilots in four Connecticut municipailites.

1 Introduction

When the State of Connecticut moved from lever voting machines to electronic voting equipment many of the processes regarding the administration of elections changed. The introduction of new voting technology made it necessary to ensure that the new procedures and safeguards were adhered

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to in all respects. To this end, the Connecticut Secretary of the State Office developed an audit process for use with this new technology. The process includes a hand-counting component and a technological component. To facilitate the development of the technological audits, the office formed a partnership with the University of Connecticut Center for Voting Technology Research (VoTeR Center), whose mission is to advise state agencies in the use of voting technologies by investigating voting solutions and equipment and developing safe use election procedures. Through this partnership the State of Connecticut has been able to continually investigate and improve upon its use of electronic voting equipment.

Our early work on evaluating electronic voting machines established that the commercially available technology falls short of guaranteeing the security of the computer-automated electoral processes. We have identified several integrity and security vulnerabilities of the available equipment and we have confirmed similar reports by other researchers. Consequently, the State introduced technological audits in its use of electronic optical scan equipment and mandated hand count post-election audits of cast ballots. It soon became evident that hand count audits, conducted at substantial cost, are time-consuming and error-prone.

Based on the results of several years of research and participation in the elections and audits in Connecticut, it was decided to consider a semi-automated approach to post-election audits. Towards this end we developed a computer-based audit station and associated auditing procedures to address the weak points of the hand counts—lack of precision and high costs of getting precise counts. The development of an automated audit station has the promise of significantly cutting the time required for the hand count, while providing a higher accuracy and efficiency. We recently completed the development of a prototype and demonstrated its utility. The project was funded in part by a grant from the U.S. Election Assistance Commission (EAC). The system was used in several pilot audit programs in Connecticut following the 2012 elections and using the actual ballots from the election. Given that optical scan systems are widely used electronic voting systems in the United States—in over 50% of the counties nationwide—the results of our development can be valuable in addressing the critical step of hand counts for more than 60 million voters (over 1,600 counties) nationwide.

Document structure. In Section 2 we describe the introduction of electronic tabulations systems, associated risks, and the mitigation in Connecticut. Section 3 presents the hand count audits instituted in the State. In Section 4 we discuss the approach to automating post-election audits. The audit station implementation is presented in Section 5.

2 Electronic Ballot Tabulation: Issues and Mitigation

Prior to deploying the optical scan voting systems in Connecticut, the Secretary of the State (SOTS) Office requested that the VoTeR Center perform an assessment of integrity and security of the chosen AccuVote Optical Scan (AV-OS) tabulators. In particular the Center was asked to evaluate a report[1] that documented a security vulnerability of AV-OS, the so-called Hursti Hack, and investigate any other vulnerabilities of the system. The investigation by the Center established that the memory cards used with AV-OS can be tampered with, thus proving the seriousness of

[1]Harri Hursti, Critical Security Issues with Diebold Optical Scan Design, Black Box Voting Project, July 4, 2005 (http://www.blackboxvoting.org/BBVreport.pdf).

the Hursti Hack. The Center also discovered new security vulnerabilities of the AV-OS system.[2] We note that if the memory cards or the AV-OS tabulators are left unattended within or without the tabulator they can be tampered with in a matter of minutes. The effects of tampering with the AV-OS and memory cards on the election outcome can be devastating: votes cast on ballots can be reassigned to arbitrary candidates, leading to invalid election results. Subsequent reports by the Center document additional integrity issues with AV-OS systems.[3,4] In particular, it was determined that even if the memory card is sealed and pre-election testing is performed, one can carry out a devastating array of attacks against an election using only off-the-shelf equipment and without having ever to access the card physically or opening the AV-OS system enclosure. It was later also determined that it is possible to inject arbitrary code by means of infected memory cards so that the entire executive can be taken over by nefarious code.[5] The attacks can cause the following: neutralizing candidates (the votes cast for a candidate are not recorded); swapping candidates (the votes cast for two candidates are swapped); biased reporting (the votes are tabulated correctly, but they are reported incorrectly using conditionally-triggered biases).

Additionally, more severe threats become possible if the tabulator is left unattended and its internals are tampered with.[6] Note that pre-election testing using vendor-provided methods may not be able to detect tampering (self-auditing is inadmissible, just as it is not admissible in the fiscal realm). The only way to guarantee that the memory cards contain valid data and programming for a particular election, is to directly examine the contents of the cards.

We also viewed certification of voting machines with skepticism. While it is tempting to view a voting terminal in isolation for the purpose of testing, it is critical to view the entire system formed by numerous voting terminals that are geographically distributed, and ultimately interacting with a central system, e.g., EMS (Election Management System), for the preparation of the election and the tabulation of the results.

Attempting to verify and certify an optical scan terminal without at the same time verifying and certifying all involved systems, including EMS, provides a false sense of security. One cannot rely on the self-test features provided by any software system because one can never trust software to test or audit itself. Independent testing and certification addresses only a part of this concern, for testing cannot guarantee correctness. In November 2006, the National Institute of Standards and Technology (NIST) concluded that unless a software system was built to be secure and reliable to begin with, "experience in testing software and systems has shown that testing to high degrees

[2]VoTeR Center, Security Assessment of the Diebold Optical Scan Voting Terminal, October 30th, 2006 (http://voter.engr.uconn.edu/voter/wp-content/uploads/uconn_report-os.pdf).

[3]A. Kiayias, L. Michel, A.C. Russell, N. Sashidar, A. See, and A.A. Shvartsman, An Authentication and Ballot Layout Attack Against an Optical Scan Voting Terminal, USENIX Electronic Voting Security Workshop (EVT07), Electronic proceedings (http://voter.engr.uconn.edu/voter/wp-content/uploads/evt07.pdf), August 2007

[4]A. Kiayias, L. Michel, A.C. Russell, N. Sashidar, A. See, A.A. Shvartsman, S. Davtyan. Tampering with Special Purpose Trusted Computing Devices: A Case Study in Optical Scan E-Voting. 23rd Annual Computer Security Applications Conference (ACSAC). Electronic proceedings. December 10-14, 2007 (http://voter.engr.uconn.edu/voter/wp-content/uploads/seea-tamperevoting.pdf).

[5]R. Jancewicz, A. Kiayias, L.D. Michel, A. Russell, A.A. Shvartsman: Malicious takeover of voting systems: arbitrary code execution on optical scan voting terminals. ACM Symposium on Applied Computing (SAC), pages 1816-1823, Coimbra, Portugal, March 18-22, 2013.

[6]S. Davtyan, S. Kentros, A. Kiayias, L.D. Michel, N.C. Nicolaou, A. Russell, A. See, N. Shashidhar, A.A. Shvartsman: Taking total control of voting systems: firmware manipulations on an optical scan voting terminal. ACM Symposium on Applied Computing (SAC), pages 2049-2053, Honolulu, Hawaii, USA, March 9-12, 2009 (http://voter.engr.uconn.edu/voter/wp-content/uploads/sac09.pdf).

of security and reliability is from a practical perspective not possible."[7]

A "certified" software-based voting machine can still be programmed to alter itself before, during, and after the election or can be subsequently manipulated with no ability for election officials or observers to perceive that the voting system has been compromised. Malicious coding can evade certification testing; the testing cannot guarantee to reveal that the code has been compromised. A certified software-driven voting system can be programmed to give the false appearance that it is in proper working order, when in fact it has been compromised.

Lastly, software systems are perpetually revised, extended and corrected. Each change, in principle, must trigger a complete new regression test, test of the changed or corrected functionality, and complete re-certification. Even if this is done, the operation of a software system can be completely changed if new data and code are added—this is in fact the case with removable memory cards that are programmed for each voting terminal before each election. The conclusion is that systematic auditing, both hand counting and technological audits, is necessary to protect the integrity of the electoral process conducted with the help of computerized election systems.

As the result of these findings, the Center recommended to the Connecticut SOTS Office that (a) strict chain-of-custody policies for AV-OS and memory cards need to be implemented, and (b) audits both technological and hand-counting need to be performed in conjunction wit elections. These recommendations have been implemented in Connecticut in 2007.

The SOTS Office asked the Center to prepare for and implement technological memory card audits for general elections that use AV-OS terminals in Connecticut. The Center developed a methodology and tools for performing technological audits[8,9] and has performed technological audits since 2007.

Optical scan voting systems are *software independent*, meaning that the accuracy and correctness of the machine count can be verified by independent means. Thus hand count audits play a major role in mitigating security and integrity risks associated with using optical scan tabulation. We next describe these audits in detail.

3 Hand Count Audit: Definition and Challenges

The hand count audit in the State of Connecticut requires an actual hand count of the ballots processed by the OS tabulators and a comparison of the hand counted results to the results provided by the OS tabulators.[10] This process after the election can detect any discrepancies between the machine counts and the actual votes cast. The audit helps ascertain the accuracy of the scanning device and the reliability of the counting process.

[7] National Institute of Standards and Technology report on computerized voting systems, NIST, http://vote.nist.gov/DraftWhitePaperOnSIinVVSG2007-20061120.pdf.

[8] T. Antonyan, S. Davtyan, S. Kentros, A. Kiayias, L. Michel, N. Nicolaou, A. Russell, and A.A. Shvartsman. Automating Voting Terminal Event Log Analysis. Proceedings of the 2009 USENIX/ACCURATE Electronic Voting Workshop (EVT/WOTE 2009), 15 pages, electronic edition, Montreal, Canada, August, 2009 (url: http://voter.engr.uconn.edu/voter/wp-content/uploads/evt09.pdf).

[9] T. Antonyan, S. Davtyan, S. Kentros, A. Kiayias, L. Michel, N. Nikolaou, A. Russell, A. A. Shvartsman. Statewide Elections, Optical Scan Voting Systems, and the Pursuit of Integrity. IEEE Transactions on Information Forensics & Security, volume 4, issue 4, pp. 597-610, December, 2009 (url: http://voter.engr.uconn.edu/voter/wp-content/uploads/ieee.pdf).

[10] For the definition of the audit see Connecticut Public Act 07-194 AN ACT CONCERNING THE INTEGRITY AND SECURITY OF THE VOTING PROCESS, approved July 5, 2007.

Mandatory post-election hand count audits are conducted by local officials in ten percent (10%) of the voting districts randomly selected to participate. The primary purpose of the hand count audit is to assess how well the optical scan voting machines functioned in an actual election and to ensure that votes cast using these machines are counted properly and accurately. Once the voting districts subject to audit are identified, each municipality sets its audit date individually. It is important to note that this procedure is not a complete recount of the election; there are separate statutory requirements for a mandated recount. The hand count audit includes only those ballots that were counted by the optical scan voting machine in the district that will be included in the audit and only in randomly-selected races. Critical in the assessment of the OS is to ensure that the hand count audit compares appropriate ballots and candidate totals to those reported by the OS. As such, certain specific requirements are necessary to ensure this comparison. First, the total number of paper ballots read by each optical scan machine should be recorded and used as a check to assure that all ballots counted by the machine are included in the audit. Second, ballots are categorized and assigned to one of the following two categories: Undisputed Ballots and Ballots with Questionable Votes. Undisputed ballots are ballots that should have been read by the optical scan voting machine. In other words, a review of the ballot in question reveals that each oval is completely filled in; there are no apparent problems, voter errors, unusual markings or noticeable stray marks in or around any of the races to be audited. Ballots with Questionable Votes are ballots that contain problems, such as voter errors (e.g., check marks in the candidates oval), or stray or unusual markings in any of the races being audited. Such problems, errors or markings may have interfered with the optical scan machines count.

Once the ballots are separated, the audit workers shall count the votes for each candidate in each of the audited races on each ballotfirst, from the Undisputed Ballots, i.e., ballots with no questionable markings; next, from the Ballots with Questionable Votes, i.e., where questionable markings appear for the particular race and candidate. The audit workers will keep separate vote totals for each candidate from both categories of ballots.

Once the hand count audit is complete, the results are reported to the Secretary of the State. Each Questionable Vote must be explained in the comments section of the audit report. If the machine total is different from the overall hand count total, then every effort must be made to investigate and explain why such is the case, including conducting a second hand count, if necessary. Any difference should be reported to the Secretary of the State. If the results of the hand count audit reveal any unexplained deviations or errors, The University of Connecticut (UConn VoTeR Center), at the request of the Secretary of the State, shall examine the machines that apparently produced incorrect results to determine if such errors were caused by the optical scan voting machine.

While playing an important role in ensuring the integrity of elections, hand count audits are not without problems. First, hand count audits are costly, tedious, and time-consuming. Second, to date, in all cases when noteworthy discrepancies were observed between the machine and hand counts, follow up investigations identified numerous hand counting errors. Based on numerous audits conducted in the State since 2007, the conclusion is that hand counting is an error-prone activity. It takes two auditors up to five hours to examine 1000 ballots, while it was observed that hand counted audit returns routinely show up to 2% error. All of this undermines the value of the hand count as an independent means of checking the correctness of tabulators.

4 Our Approach to Automating Audits

Before attempting any approach to automating post-election audits, it is important to consider the question of whether hand count audits can or should be automated. Given the challenges and issues with hand count audits, it is tempting to develop a completely automated approach. However, there are serious concerns associated with the use of automation in post-election audits if the human auditors are prevented or excluded from being meaningfully involved in the audit procedure: *Quis custodiet ipsos custodes?*[11] For example, some proposals to automate audits permit the use of the same equipment to tabulate the ballots. This is clearly problematic: using the same tabulator, or even a different tabulator of the same design will not reveal problems that cause similar errors in interpretation, or even complete misinterpretation of ballots. Using equipment or software from the same vendor, or using equipment from a different vendor to perform completely automated retabulation of ballots is also problematic for similar reasons. In general, any opaque, unobservable, or unobserved automated auditing presents problems due to the fact that the only primary document in the election, that is, the voter-generated paper ballot, is never inspected by the audit officials. Automated audit systems that analyze ballot images and that separation ballot images from ballots are likewise troublesome. This is because "a subverted retabulation system could display arbitrarily many ballot images and correct interpretations thereof, yet every vote count could be misreported."[12] In general, any completely automated audit system where human auditors delegate all responsibility for the audit to automation cannot be recommended as a valid approach to retabulation. To sum it up, "relying on unaudited retabulations is dangerous and unwarranted."[13]

Nevertheless, given the cost, time, and accuracy concerns plaguing purely manual audits, it is desirable to provide some automation in assisting post-election audits. What kind of automation can be sensibly deployed? We consider it reasonable to provide the *semi-automated* means for assisting audits that are not subject to the same flaws as those found in the completely automated or unaudited approaches.

In 2011 the State of Connecticut began considering the introduction of automation to improve the accuracy and speed of post-election ballot audits, while reducing the audit costs. In collaboration with the University of Connecticut Center for Voting Technology Research, the Secretary of the State Office formulated a plan for developing and experimenting with a semi-automated *Audit Station*. The plan became a part of a successful proposal submitted by the State of Connecticut to the U.S. Election Assistance Commission (EAC), and the funding provided partial support for design, development, and pilot deployment of the Audit Station. The main goal of the project is to specify, develop and validate a novel audit station that will enable fully independent counting and tallying of the election results. An independent Audit Station will assuage concerns about the validity of machine counting and significantly reduce the issues associated with error-prone human counting. With new and improved post-election auditing procedures the State hopes to increase the accuracy and reduce the amount of time and cost that Connecticut municipalities currently incur when they perform the current post-election audit of the results reported by the voting machines. As a tool for auditors, it is expected that ultimately it will be deployed broadly in Connecticut in the post-election audits.

[11](Latin) *Who will watch the watchmen?*

[12]Mark Lindeman, Ronald L. Rivest, and Philip B. Stark. Retabulations, Machine-Assisted Audits, and Election Verification. 20 March 2013 (`http://www.stat.berkeley.edu/~stark/Preprints/retabulation13.htm`).

[13]Ibid.

The vision for the Audit Station is a combination of hardware, software, methodology and auditing procedures for automating the post-election ballot counting activities. The following overall list of requirements (non-exaustive and in no particular order, but with some intentional redundancies) guides the development of the Audit Station for optical scan tabulators.

(a) The system must implement semi-automated audits with complete human control: the human auditors must be able to be the final arbiters of the results of each ballot interpretation.

(b) The system must support auditing of ballots in small batches without the need to precount the number of ballots.

(c) The system must be able to audit all races in an election in a single pass of the audit process.

(d) Any batch can be processed as many times as is considered necessary by the human auditors.

(e) The system must support auditing of optical scan voting tabulators, in particular, it is sufficient for it to consider any marks in the voting areas (or "bubbles") that are to be considered by the actual tabulator in a specific election.

(f) The system must maintain tight coupling between between the physical ballots and their automated interpretation.

(g) The system may not separate individual votes from the ballot: in particular, any vote recorded on the ballot must always be considered in the context of the ballot.

(h) The auditors must be able to specify thresholds determining the criteria for what constitutes a vote.

(i) The system must alert the auditors to the existence of any "ambiguous" or "questionable" marks that fall outside of the auditor-specified thresholds.

(j) The auditors must be able to easily compare the result of automatic interpretation and the result of their own examination of each ballot.

(k) The system's interpretation of each ballot is merely a suggestion to the human auditors: the audits must be able to easily override the suggested interpretation.

(l) The system must support a fast "sanity check" analysis of a batch as well as an individual examination of each ballot in the batch.

(m) Automated analysis of ballots must be able to achieve performance rates of up to 100 two-sided ballot sheets per minute using a single scanner (with the rate of analysis limited only by the scanner capability).

(n) The system must be able to operate on inexpensive commercial off-the-self components (COTS).

(o) The semi-automated process must be able to match the results of an accurate hand count at substantial savings in time and effort.

(p) The auditing process must be easily observed by the audit officials and the interested public.

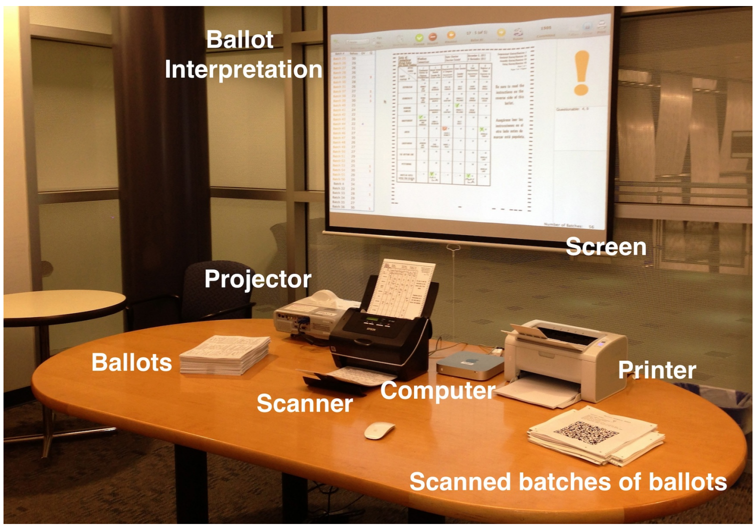
(q) The system must commit and export the interpretation of each ballot as well as the overall results for independent verification.

We next present the system that resulted from our development.

5 Audit Station at a High Level

Auditing involves automatic scanning of ballots in batches, where each ballot, and its suggested interpretation, is projected onto a large screen for auditors and the interested public to observe. Using auditor-specified definitions, the system identifies unambiguous and questionable votes and presents this information by means of color-coded overlays on the ballots. The auditors can accept the automatic interpretation, or they can override it. Each batch can be scanned multiple times to increase the auditors confidence as needed.

The Audit Station, as presented here, was used in four pilot audits in the State of Connecticut.



The system consists of the following main hardware components: 1) optical scanner, 2) computer, 3) printer, 4) and projector.
In the audit mode, the system projects an image of the ballot together with its interpretation.

Figure 1: Audit Station setup

The setup of the Audit Station is shown in Figure 1. Each hardware component is a relatively inexpensive COTS component. In this paper we do not describe these components in detail and we do not delve into technical decisions that led to the selection of the computing platform. We mention that the current system runs on a mid-range Apple Mac mini and it can include any optical scanner that supports standard interfaces.

The scanner in the figure is an inexpensive Epson GT-S80 model with which we achieve rates of up to 40 two-sided ballots per minute (this rate is currently only limited by the capability of the scanner). In supporting the batch-oriented audit process, it is most convenient to limit the size of the batch to the capacity of the automatic feeder in the scanner (the system with the shown scanner handles up to 40 ballots at a time).

Likewise, any standard computer projector can be used, and the screen is optional as the projector works quite nicely with any lightly colored wall. Note that no computer monitor is needed, since the projector also serves as the monitor. The setup shown in the figure is compact and it was easily transported for the audit pilots that we conducted in several Connecticut towns.

6 The Audit Process

We now outline the audit process in greater detail. The computer-assisted audit process is designed to be used in conjunction with the post-election ballot audits in a polling district (precinct). The process assumes a batch-oriented approach, where all ballots in a district are divided into small batches, with each batch tabulated with the help of the audit station. The auditors can make decisions for any ballot on whether to accept the cast votes as analyzed by the Audit Station, or to revise the votes. The overall audit process is as follows.

1. Once a specific district is chosen for the post-election audit, the Audit Station is configured to audit the particular district using the official ballot definitions. (We do not present this function in detail. The systems is designed to support an administrative interface that is used to prepare the system for the audit. This includes providing a ballot definition to the system and annotating it as necessary. Ultimately the information for the ballot definition will be obtained from four different sources: memory card of the optical tabulator, pdf file of the ballot, scanned ballot image, and the election management system database.)

2. On the day of the audit, the Audit Station is delivered to the district. The thresholds for determining what constitutes a "vote" and what constitutes a blank, unvoted bubble are initialized at the district.

3. The ballots are divided into batches. No pre-counting of the ballots is necessary—the auditors simply separate a deck of ballots based on its thickness to approximate teh desired size.

4. Scanning a batch:

   (a) A batch is scanned using the Audit Station using one of the two modes described above.

   (b) If this is the first time the batch is processed, after the last ballot of the batch, the Audit Station generates a batch cover sheet that contains a unique batch sequence number. The cover sheet is human readable as well as encoded using a QR code.

   (c) The batch cover sheet is placed on top of its batch. This is used to identify the batch if it is to be examined manually or rescanned using the Audit Station.

   (d) If the Audit Station determines that some votes are ambiguous or cannot be processed, the auditors are informed. In any case, each scanned ballot can be compared with the corresponding paper ballot, and the auditors can revise the ballot interpretation and/or rescan the batch.

   (e) Once the auditors accepted and commit the results for a batch, the Audit Station adds the totals from the batch to the election totals (replacing the previous interpretation of this batch, if this is not the first scan of the batch). The Audit Station displays the running election totals and the most recently scanned batch totals.

5. Any batch can be rescanned as many times as necessary. Each rescan of a batch produces a new result for the batch that overrides the results of any previous scan. For a rescan, ballots can be added to or removed from any batch that has not been committed by the auditors.

6. After all batches have been scanned, processed, and committed, the Audit Station produces the final tally based on the internally stored summaries. The Audit Station also exports the results for each ballot, each batch, and the overall totals for independent verification, depending on the official procedures (in particular, this enables the system itself to be audited

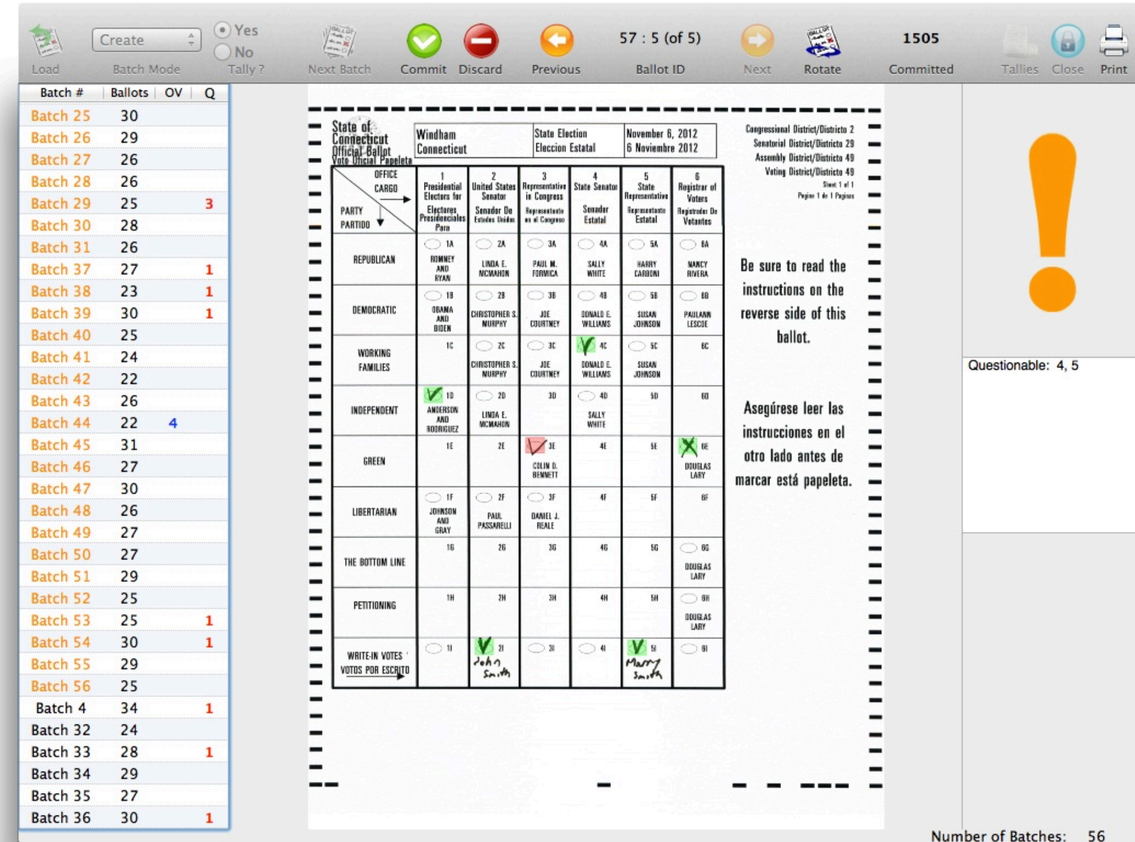


Figure 2: Audit Station ballot interpretation:

in the style risk-limiting audits[14]). Once this is done the results of the audit cannot be altered/revised using the Audit Station. (If changing the results is necessary, the enture district needs to be re-audited.)

We note that the decisions on the deployment logistics of the Audit Station and associated methodology have not been finalized, thus our presentation focuses on the selected capabilities of the system. We next provide additional details of the audit process.

7 Audit Station Details of the User Interaction

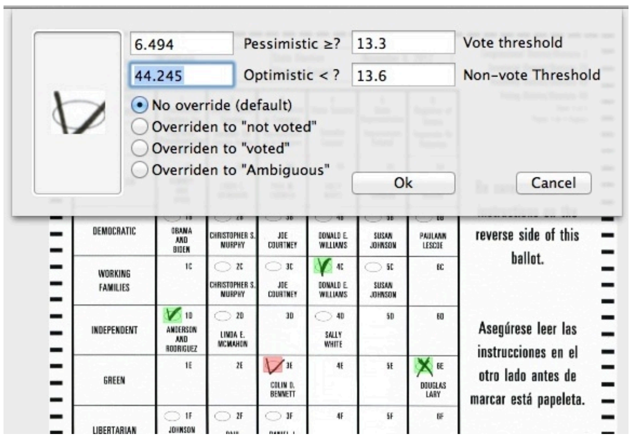
Ballot interpretation display. For each ballot in a batch the Audit Station displays the ballot interpretation as the ballots are being scanned. The auditors can page through the ballots in a batch to examine the interpretation, to compare the interpretation to the physical paper ballots in the batch, and to override the interpretation.

Figure 2 shows the automatic interpretation of the votes recorded on a ballot. The system uses a color-coded transparent overlay to show the automatically derived vote interpretations. The large

[14]Cf. M. Lindeman and P.B. Stark. A Gentle Introduction to Risk-limiting Audits. In *IEEE Security & Privacy, Special Issue on Lectronic Voting*. IEEE, march 2012.

exclamation sign indicates that the batch contains questionable votes on ballots 4 and 5, as shown below the sign. The currently displayed ballot is number 5 in the batch. The system identifies votes based on the thresholds set by the auditors; the interpretation is shown the color overlay. The marks that exceed the voted threshold are colored green by the system. The marks in the voting areas that are above the blank threshold but below the voted threshold are colored red.

Figure 3 shows the vote override interface. When the auditors examine a scanned ballot, they can override the interpretation of any bubble (vote area). If a vote interpretation is overridden, the system includes and displays an annotation in the ballot overlay.



The ballot number 5 in the current batch number 57 from Figure 2 contains a mark that the Audit Station considers ambiguous; it is highlighted red by the system. The auditor selected the corresponding bubble for inspection. The voting area is magnified and the system also displays the relevant thresholds and the score obtained by the mark. The auditors can now accept the automatic interpretation, or override it. The override can be done using any of the three choices: not voted, voted, or ambiguous.

Figure 3: Examining and overriding automatic interpretation.

Batch processing details. We now describe the processing of a batch in more detail. A batch is any collection of ballots, where any ballot can belong to only one batch at a time. Setting a sensible maximum number of ballots in a batch should reflect the common opinion that "small-batch auditing" is desirable. We found it convenient to limit the maximum size of the batch not exceed the capacity of the scanner's automatic feeder (e.g., up to 40 ballots). Using larger size batches is of course possible, but this requires that a larger batch is fed through the scanner in smaller sub-batches suitable for the scanner.

The audit of each batch can be done in one of two modes: (1) a batch is scanned automatically, then the ballot interpretations are browsed by the auditors, so that each ballot interpretation is examined and revised by the auditors as needed, or (2) the ballots in the batch are scanned one at a time, with the audit station pausing after each ballot, to let the auditors observe the results of the scan for each ballot. The first process is faster, while the second process provides an easier way for comparing the results of the automatic interpretation to the physical ballots.

Once a batch is scanned and processed, the system display the batch summary as shown in Figure 4. All races in the election are counted at the same time. Recall that any batch can be re-scanned if deemed necessary, and as many time as the auditors consider necessary. When a batch is processed for the first time, its identifier is given in a light (orange) font in the left pane of the display. When two consecutive scans of the same batch yield identical results, the color is changed to black. The auditors can always commit the batch results based on the most recent scan, overriding all prior interpretations.

Finally we note that the system allows for multiple audit stations to be used in parallel in the same district level audit. The system automatically aggregates the results of the batch processing at different stations.

Audit summary. The Audit Station maintains an audit summary that provides a cumulative view of the batches scanned thus far. An example of the summary display is in Figure 5. Batch summaries are displayed in the left pane. The status of each batch is indicated by the font color (orange or black as described earlier) in the column labeled Batch #. The column labeled Ballots gives the number of ballots in each batch. The column labled OV deals shows the number of overvoted ballots. The number of questionable bubbles is given per batch in the column labeled Q.

Technical issues. Several technical issues were resolved during the development of the Audit Station. We have considered and evaluated three system platforms for this development (Windows, Unix, and Mac), and we have settled on the Mac platform as the most suitable. This determination was made on the basis of the platforms ability to support effective user interface development, its support for a variety of scanners, and its support of suitable image processing software.

Image Processing. We designed and evaluating algorithmic approaches to image correction and analysis. We have established that, depending on the type and make of scanners, the scanned images are distorted. This distortion is typically piecewise linear in the length of the scanned image (ballot). Our algorithms have been designed to correct the scanned image, including de-skewing, so that the digitized image is a faithful representation of the correctly printed ballot. We also developed algorithms that enable fast ballot analysis, with the goal of enabling scanning rates up

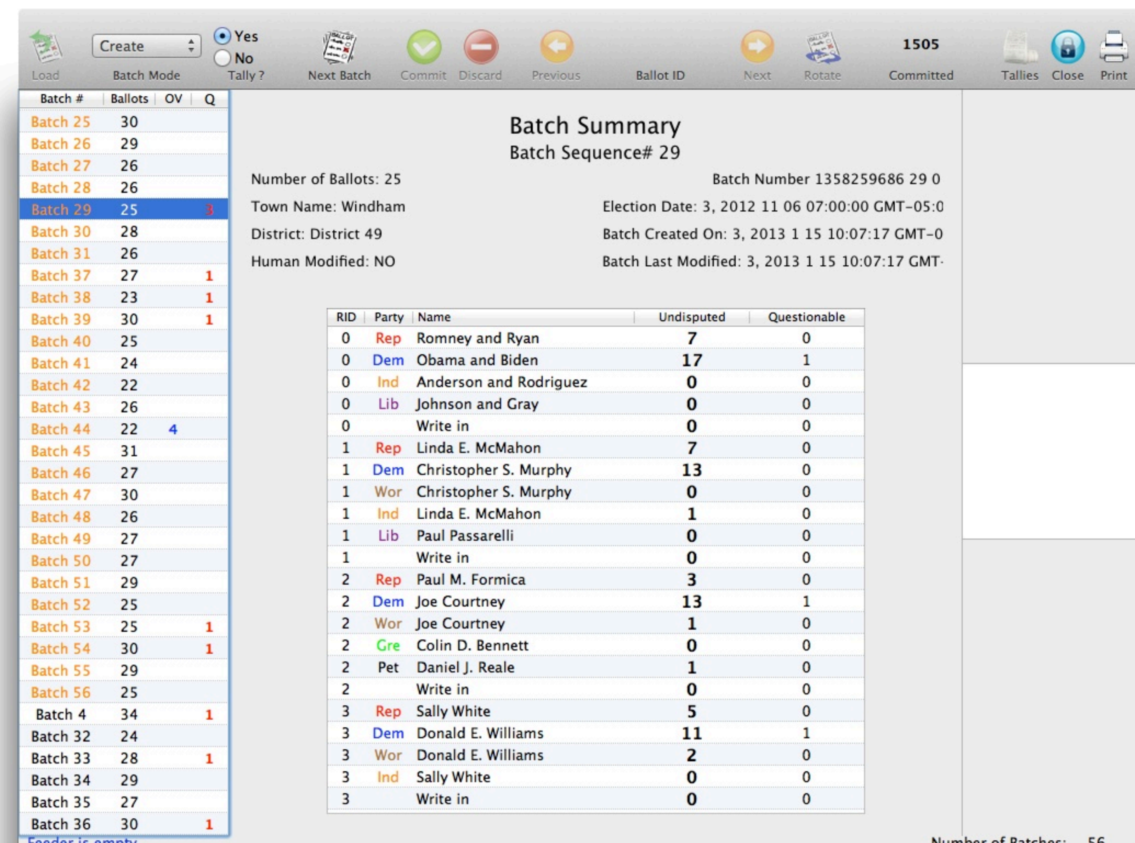


Figure 4: Batch summary display: the totals are given for the selected batch in the left column.

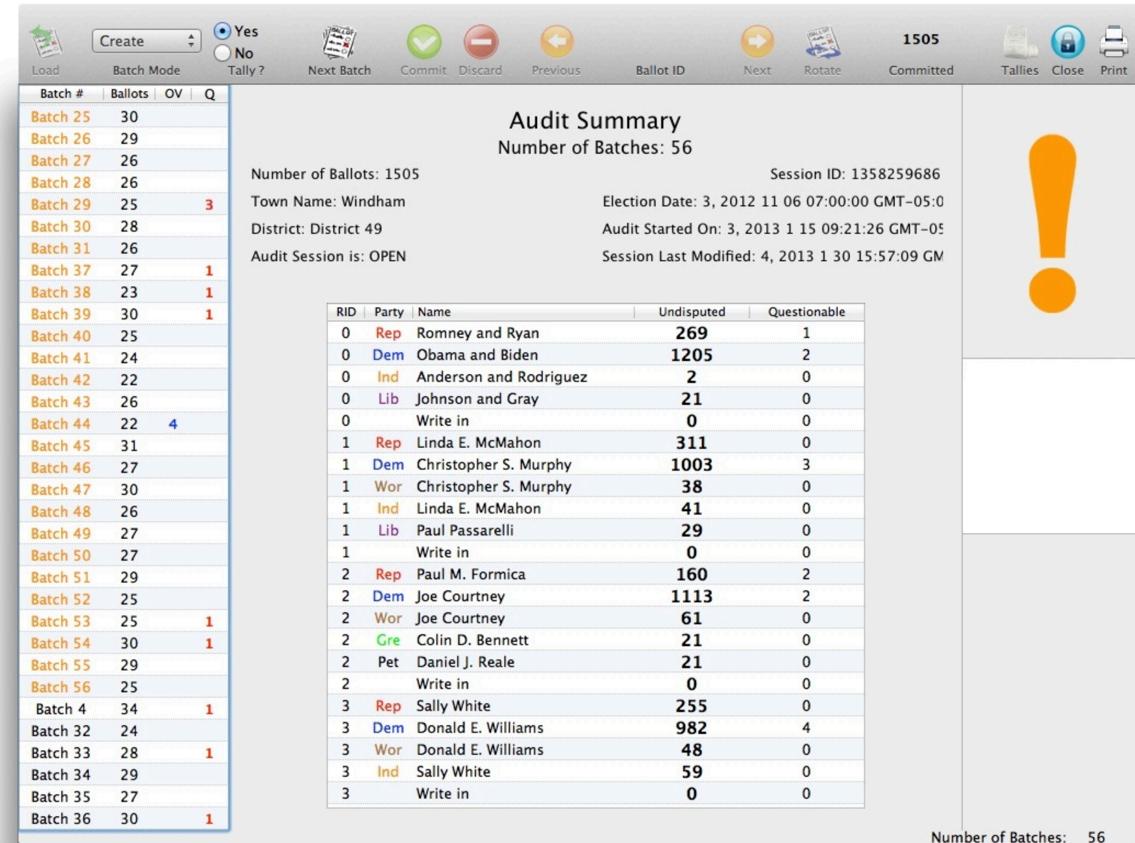


Figure 5: Audit summary display: here in the left column the committed batches are shown in the black font and the tentative batches are in a light font; the large "!" sign indicates that there are ambiguous votes in the election that may need to be resolved.

to the ability of the specific scanner. Using the current scanner, we are able to push it to its limit of about 40 ballots per minute. We are planning to integrate commercial scanners that will enable up to 100 ballots per minute scanning rates, but the availability of such (affordable) scanners is an issue, and the vendor software support for such scanners is not sufficient for fast adoption.

Scanner Certification. Given that the Audit Station is designed as a turnkey solution, we intend to certify scanners for integration. In order to ensure the most faithful ballot image capture, we are developing techniques for evaluating scanners, and specifying scanner "signatures" to be included with our software. Given that different scanners have different scanning characteristics, only the scanners for which we develop signatures may be include in the Audit Station solution. Such a diligent approach is necessary to prevent the possible interference of scanner hardware variations from affecting the quality of captured ballot images.

Of independent interest, we note that our software accurizing of scanners allows for inexpensive commercial scanner to be used with high precision, comparable to that achievable in expensive scanners. Additionally, our efficient image processing algorithms enable fast processing of ballots using a modest overall off-the-shelf computer system.

A forthcoming report will cover the technical details of the Audit Station implementation.

8 Audit Station Pilots in Connecticut

The Audit Station was deployed in auditing pilots in four municipalities in Connecticut using the actual ballots from the November 2012 elections. In each case ballots from one district were audited, where from about 2,000 to 3,800 ballots were processed depending on the district. The total ballot counts matched the official counts, except for one case that was apparently due to a single misplaced ballot. The summary of the audits is in Table 1.

Town	Number of Ballots	Hand Count Total Hours	Audit Station Total Hours	% Savings
Tolland	3851	48	14	70%
Bloomfield	2272	40	7	80%
Windham	1963	n/a	5	n/a
Vernon	2544	79	7	90%

Table 1: Summary of the number of ballots audited and the number of hours spend on audits.

In the towns of Tolland, Bloomfield, and Vernon official hand counts were performed prior to the Audit Station pilot. In each case we recorded the total number of hours spent doing the pilot audits. Given that the total number of hours spent in the official audit is available for the three municipalities, we observe that at least 70% savings in time were achieved using the Audit Station.

During each audit, we compared the official tally (and the official election-day hand count data where applicable) to the results obtained using the Audit Station. This summarized in Tables 2, 3, 4, and 5. In the tables the column labeled Official Count reports the official tabulator count, the column Audit Station Count reports the counts obtained using the Audit Station, the column Hand Counted Ballots reports the counts resulting from the ballots hand counted in the official election (if any), and, in the cases where there were hand-counted ballots, the column Total reports the sum of the Audit Station Count and Hand Counted Ballots. Note that in the State of Connecticut a candidate may be cross-endorsed by multiple parties. Voting for the same candidate along more than one party line contributes one vote to the candidate, and is not considered to be an overvote. Thus the significant totals are in the lines where the candidate's name is followed by the tag TOT.

9 Conclusions

To safeguard the integrity and security of the electoral process conducted using optical scan tabulators, a comprehensive approach is being pursued in Connecticut that includes technological audits and post-election hand-counted audits. Observing that the hand-counted audits are time-consuming, labor-intensive, and error-pone, it was decided to explore a semi-automated approach to post-election ballot audits. This led to the development of the Audit Station. The system speeds up the audit process, increases audit accuracy, and most importantly, empowers the human auditors to have complete control over the audit down to the interpretation of each voted "bubble." The system is implemented using inexpensive commercial off-the-self components, and is equipped with a projector that enables the auditors (and the public) to observe the audit process and to override it as necessary. The system itself can be audited using its committed data. The Audit Station was used in successful pilots in four Connecticut municipailites. Overall, we found that it significantly decreases the effort needed to conduct post-election audits, while providing excellent accuracy and allowing the human auditors to maintain as much control as they desire over the audit process.

	Tolland Official Count	Audit Station Count	Hand Counted Ballots	Total
Ballot Count	3851	3847	4	3851
Presidential Electors for				
Romney/Ryan	1822	1821	1	1822
Obama/Biden	**1956**	1953	2	**1955**
Anderson/Rodriguez	25	25		25
Johnson/Gray	34	34		34
Write-In	8	7	1	8
United States Senator				
Linda E. McMahon REP	1702	1737	1	1738
Linda E. McMahon IND	93	93		93
Linda E. McMahon UNK	36			
Linda E. McMahon TOT	1831	1830	1	1831
Christopher Murphy DEM	1753	1782		1782
Christopher Murphy WKF	76	76		76
Christopher Murphy UNK	31			
Christopher Murphy TOT	1860	1858	2	1860
Paul Passarelli	95	94	1	95
Write-In	3	3		3
Representative in Congress				
Paul M. Formica	**1192**	1190	1	**1191**
Joe Courtney DEM	2263	2306	3	2309
Joe Courtney WKF	168	166		166
Joe Courtney UNK	45			
Joe Courtney TOT	**2476**	2472		**2475**
Colin D. Bennett	38	38		38
Daniel J. Reale	24	24		24
Write-In	0	0		0
State Senator				
Tony Guglielmo	**2467**	2463	3	**2466**
Susan Eastwood DEM	1164	1181	1	1182
Susan Eastwood WKF	66	66		66
Susan Eastwood UNK	16			
Susan Eastwood TOT	1248	1247		1248
Write-In	1	1		1
State Representative				
Christine Vincent	1423	1422	1	1423
Bryan Hurlburt	2266	2263	3	2266
Write-In	1	1		1
Registrar of Voters				
Kenneth R. Houck	1615	1614	1	1615
R. Michael Wyman	**1947**	1946	2	**1948**
Write-In	3	2	1	3
Question 1				
Yes	2264	2260	4	2264
No	1361	1361		1361

Table 2: Tolland audit results

	Bloomfield Official Count	**Audit Station Count**
Ballot Count	2272	2272
Presidential Electors for		
Romney/Ryan	389	389
Obama/Biden	1865	1865
Anderson/Rodriguez	3	3
Johnson/Gray	7	7
Write-In	6	6
United States Senator		
Linda E. McMahon REP	400	407
Linda E. McMahon IND	35	35
Linda E. McMahon UNK	7	
Linda E. McMahon TOT	442	442
Christopher Murphy DEM	1605	1707
Christopher Murphy WKF	48	48
Christopher Murphy UNK	102	
Christopher Murphy TOT	1755	1755
Paul Passarelli	22	22
Write-In	1	1
Representative in Congress		
John Henry Decker REP	**302**	**301**
John B. Larson DEM	1693	1793
John B. Larson WKF	54	54
John B. LarsonUNK	70	
John B. Larson TOT	1817	1817
S. Michael DeRosa GRN	31	31
Matthew M. Corey PET	**14**	**15**
Write-In	0	0
State Senator		
Malvi Garcia Lennon REP	329	329
Malvi Garcia Lennon IND	37	37
Malvi Garcia Lennon UNK	0	
Malvi Garcia Lennon TOT	366	366
Eric D. Coleman DEM	1636	1720
Eric D. Coleman WKF	64	64
Eric D. Coleman UNK	84	
Eric D. Coleman TOT	1784	1784
Write-In	0	0
State Representative		
Quentin E. Johnson REP	312	312
David A. Baram DEM	1703	1779
David A. Baram WKF	53	53
David A. Baram UNK	75	
David A. Baram TOT	**1831**	**1832**
Write-In		
Registrar of Voters		
Barbara Reisner	409	409
Anne Wall	**1669**	**1670**
Write-In	0	0
Question 1		
Yes	1325	1325
No	462	462

Table 3: Bloomfield audit results (there were no ballots hand-counted in the official election).

	Windham Official Count	Audit Station Count	Hand Counted Ballots	Total
Ballot Count	**1963**	1963	1	**1964**
Presidential Electors for				
Romney/Ryan	**356**	**357**		
Obama/Biden	1552	1552		
Anderson/Rodriguez	6	6		
Johnson/Gray	34	33	1	34
Write-In	10	10		
United States Senator				
Linda E. McMahon REP	406	417		
Linda E. McMahon IND	54	54		
Linda E. McMahon UNK	10			
Linda E. McMahon TOT	**470**	**471**		
Christopher Murphy DEM	1250	1287		
Christopher Murphy WKF	58	58		
Christopher Murphy UNK	36			
Christopher Murphy TOT	**1344**	**1345**		
Paul Passarelli	42	41	1	42
Write-In	3	3		
Representative in Congress				
Paul M. Formica	**225**	**226**		
Joe Courtney DEM	1399	1423		
Joe Courtney WKF	85	85		
Joe Courtney UNK	23			
Joe Courtney TOT	**1507**	**1508**		
Colin D. Bennett	30	30		
Daniel J. Reale	29	28	1	29
Write-In	1	1		
State Senator				
Sally White REP	342	345		
Sally White IND	76	76		
Sally White UNK	2			
Sally White TOT	**420**	**421**		
Donald William DEM	1253	1265		
Donald William WKF	65	65		
Donald William UNK	12			
Donald William TOT	1330	1330		
Write-In	1	0	1	1
State Representative				
Harry Carboni REP	**320**	**322**		
Susan Johnson DEM	1327	1351		
Susan Johnson WKF	107	107		
Susan Johnson UNK	23			
Susan Johnson TOT	**1457**	**1458**		
Write-In				
Registrar of Voters				
Nancy Rivera REP	**343**	**345**		
PaulAnn Lescoe DEM	**1185**	**1186**		
Douglas Lary GRN	160	166		
Douglas Lary TBL	16	17		
Douglas Lary PET	8	8		
Douglas Lary UNK	7			
Douglas Lary TOT	191	191		
Write-In	3	2	1	3

Table 4: Windham audit results (where there were no hand-counted ballots, the total is the same as the Audit Station Count).

	Vernon Official Count	Audit Station Count
Ballot Count	2544	2544
Presidential Electors for		
Romney/Ryan	1010	1010
Obama/Biden	1488	1488
Anderson/Rodriguez	12	12
Johnson/Gray	20	20
Write-In	10	10
United States Senator		
Linda E. McMahon REP	926	953
Linda E. McMahon IND	88	88
Linda E. McMahon UNK	27	
Linda E. McMahon TOT	1041	1041
Christopher Murphy DEM	1248	1298
Christopher Murphy WKF	63	63
Christopher Murphy UNK	50	
Christopher Murphy TOT	1361	1361
Paul Passarelli	60	60
Write-In	8	8
Representative in Congress		
Paul M. Formica	649	649
Joe Courtney DEM	1574	1636
Joe Courtney WKF	136	136
Joe Courtney UNK	62	
Joe Courtney TOT	1772	1772
Colin D. Bennett	27	27
Daniel J. Reale	17	17
Write-In	2	2
State Senator		
Tony Guglielmo	1299	1299
Susan Eastwood DEM	1023	1041
Susan Eastwood WKF	61	61
Susan Eastwood UNK	18	
Susan Eastwood TOT	1102	1102
Write-In	2	2
State Representative		
Claire L. Janowski DEM	1840	1840
Write-In	28	28
Registrar of Voters		
Cynthia A. Madden REP	950	950
Judith A. Beaudreau DEM	1295	1295
Write-In	3	3

Table 5: Vernon audit results (no manual count was done in this municipality).