



Interdisciplinary Research Experiences for Undergraduates in Metrology and Non-Destructive Inspection

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Abstract

The objective of this paper is to outline the quick startup procedures involved in establishing a new National Science Foundation (NSF) Research Experiences for Undergraduates (REU) site, and to detail year-one's major activities, results, impressions, and lessons learned. The insights gained during year-one, are now being implemented to further improve the site operation and performance for a sustained and broader impact during the upcoming years.

The overarching goal of this site was to enhance the knowledge and skill-level of a diverse cohort of undergraduates with limited access to research opportunities, through empowering, hands-on and interdisciplinary research experiences in both traditional and advanced metrology and non-destructive inspection (NDI) technologies. Metrology, the science of measurement, and (nondestructive) inspection transcends scales, materials, and disciplines; yet, rarely are its salient aspects emphasized. This site is a first-of-its-kind direct response to a specific concern raised by regional industry partners and technical workforce recruiters about the lack of pragmatic metrology/NDI-related knowledge and skills in their incoming regional workforce. For this, 5 vertically-integrated teams, each comprising of 2 REU students, 1 senior undergraduate and 1 graduate student (from the host institution) and a faculty mentor worked in concert on select research projects over 10 summer-weeks. Each REU student pair was recruited and matched based on complementing skills/interests. This onsite experience was supplemented with follow-ups for continued interaction, growth, and guidance for pursuing advanced study. The overall impact of this site was to create empowered future researchers and a workforce well-rooted in metrology/NDI, and motivate them to pursue advanced degrees.

The PI's experience of going through a quick startup and establishment of this site shed light on the strategies and essentials needed for generating a sufficient and diverse applicant pool, quick recruitment procedures, the logistics involved before, during and after the program, and the overall vision needed to provide a fruitful research experience to the visiting undergraduates. Evaluation mechanisms consisted of pre- and post- questionnaires, and the product deliverables. These provided invaluable insight into student impressions of the site performance, their own performance and related aspects of metacognition as well as the effectiveness of vertically-integrated teams, besides a confirmation and/or an invigorated intent to pursue advanced study and a career in STEM fields. Altogether, the experience and lessons learned from year-one has provided invaluable perception for imparting a broader impact through this NSF-REU site.

Background & Motivation

Metrology, the science of measurement, and (non-destructive) inspection transcends scales, materials, and disciplines; yet, rarely are its salient aspects emphasized. For instance, is it alarming that a significant number of graduating seniors in engineering are oblivious to errors and uncertainty in measurement, gauge repeatability/reproducibility, fits/tolerances, etc., such that they are perplexed as to why a computer-aided design (CAD) model of a 2" diameter cylinder will fit in a 2" diameter hole model just fine, but the physically fabricated pieces don't.

Though some engineering programs offer some metrology/NDI related detail in their curriculum, often, these are treated only nominally and any associated labs are uncommon. Even though these should be critically emphasized in the engineering curriculum, it is rarely so as the available time/resources are already scarce to even cover common core courses and major-specific fundamentals. Besides, the metrology/NDI field has significantly and rapidly expanded with the advances in computing and advanced materials/manufacturing, thus rendering a comprehensive treatment infeasible in terms of the time available and costs involved in acquiring, housing and maintaining the equipment. This scenario often results in (if any) metrology/NDI equipment available for student exposure and training to be very limited in terms of type, quantity and relevance, thus crippling students in both related knowledge/skills.

In stark contrast, such equipment/techniques that are in prevalence today especially in the energy and manufacturing industry (*e.g.*, oil/gas, aerospace, nuclear), government research labs (*e.g.*, NIST), etc. are typically state-of-the-art. This predominantly a due to the fact that accurate scientific measurement/inspection is the critical cornerstone for quality, innovation and improvement. Thus, a major disconnect between the knowledge/capabilities of the incoming workforce and the requirements of the job exists.

In order to bridge this gap, this new REU site was created as a direct response to specific concerns raised by regional industry partners, technical workforce recruiters, as well as by faculty that teach the relevant courses/labs – this recurring theme which has been consistently brought up over the years was that graduating senior undergraduates, who essentially constitute the incoming regional workforce and/or graduate degree pursuers, do not exhibit the necessary and pragmatic knowledge/skills in metrology and NDI. Such feedback was also echoed by both small/large regional energy and manufacturing industry partners that predominantly hire STEM students, and particularly by the Industrial Advisory Boards of engineering departments across the Texas A&M University (TAMU) System (a network of 11 universities, serving about 131,000 students).

Targeted Student Populations

The primary target region for student participant recruitment included the south-central states. These states have economies that are rapidly growing in the energy and manufacturing sectors, and hence were ideal candidate locations to recruit students from; this suited the REU site focus on metrology/NDI, which is a critical and universal component of these industry sectors. In order to kick-start the project's first year cycle, institutions in the neighborhood of TAMU (east-TX) were especially targeted, so as to leverage the TAMU faculty team's existing relationships. This included the Houston-Austin-Dallas triangle, encompassing the top three (3) of '*America's Fastest-Growing Cities in 2015*' (Forbes [1]), as well as two (2) cities in the top five (5) of the '*Fastest Growing Manufacturing Metros*' (BizJournals [2]).

Given the interdisciplinary site focus, the target academic majors included those of the faculty mentors themselves; namely, materials, manufacturing, mechanical, petroleum, and industrial engineering. The target academic-levels spanned freshmen to seniors in 4-year institutions and 2-year community colleges, and also outstanding high school graduates are slated to start his/her degree at these institutions. Such a proactive approach was to help retain a critical group of students who are at the cusp of selecting (or eliminating) a major, and hence STEM careers.

REU Site Objectives & Activities

The objectives of the REU site were to enhance the knowledge and skills of 30+ undergraduate students through empowering, hands-on and interdisciplinary research experiences in both traditional and advanced metrology and NDI technologies. Primarily serving as a vehicle to meet the critical need that is lacking in the region, this was the first-of-its-kind site that placed emphasis on the major aspects of scientific measurement and inspection, especially in relevance to the energy and manufacturing sectors. The intended site goals were:

1. To excite, empower and educate undergraduates in traditional/advanced metrology/NDI,
2. For them to experience an immersive research-training through a transformative project,
3. To mold them as independent/collaborative researchers and effective communicators,
4. For them to learn to ask the right questions, formulate plans, pragmatically interpret data,
5. To inspire and enable them to pursue advanced study and related STEM careers.

Organizational Structure:

In lieu of the typical exclusive one-on-one mentoring of undergraduate students, this site utilized and extended the vertically-integrated team framework for a more realistic, meaningful and effective engagement of undergraduates in research. Initiated by Georgia Tech in 2009, Vertically-Integrated Projects (VIP) unite undergraduate education and faculty research in a team-based context, where students earn academic credits and/or a research experience, while furthering discovery [3]. The effectiveness of such multidisciplinary [4], and mixing of multi-level students [5] has been demonstrated [5-8], and adopted widely as a result [9-11].

At TAMU, five (5) such vertically-integrated teams were assembled, each collectively tackling a research problem over summer, while functioning within each mentor faculty's externally-funded (larger) research group, in addition to one-on-one mentoring. To the extent possible, each REU student pair was recruited and suitably matched based on complementing skills and interests, one a junior/senior, and that other a younger counterpart. Thus, each team comprised of two (2) matched REU students, one (1) senior undergraduate TAMU student from each mentor faculty's research group, one (1) graduate student to coordinate day-to-day research activities and ensure safety, and one (1) faculty mentor directing the VIP team.

At this juncture, it is to be noted that it is important to be an independent thinker, while at the same time being able to collaboratively work and leverage the strength of a focused group. Both these polar qualities are essential for a researcher, and hence balancing individual ownership of the project while leveraging the collective group synergy was explicitly stressed, and mutually inclusive/exclusive task-sets were defined so as to draw from both levels. Thus, the overarching intended student outcome of this site was expected to be that, when faced with a technical problem, the students will be able to ask the right research questions, formulate an educated solution plan, using the resources available, leverage the group synergy, and attain growth.

Year-1 Site Startup & Establishment

Due to the award notification from NSF officially coming through only a couple of months before the proposed program commencement date, the principal investigators had to expedite the process of starting up and establishing the new REU site. For this, while the post-award procedures were being finalized and worked out at and between the federal and university institutions, the most time-critical component was identified and advanced; this was the process

of advertising the site opportunity and soliciting potential student participant applications. A public webpage and flyer was created for this purpose, taking cues from other established and successful sites. Recruitment efforts leveraged several channels including, but not limited to:

- Engineering Academic & Student Affairs (EASA): TAMU EASA had existing resources and infrastructure to reach out to external undergraduate students, and used its websites, brochures, electronic newsletters and announcements to advertise in the region.
- Professional societies: Local student and professional chapters of the Society of Manufacturing Engineers (SME), American Society for Engineering Education (ASEE), and American Society of Mechanical Engineers (ASME) were leveraged to disseminate the opportunity through emails, listservs, respective websites, and at regional meetings.
- Institution visits: Site visits to a number of regional target institutions we conducted to present the program, invite potential participants, and discuss available resources.
- Personal contact: Phone calls/emails to faculty contacts at regional institutions were made including community colleges and HCBUs with high underrepresented populations.

From among these, the approach that proved most effective in generating student application submissions included forwarding the opportunity to and requesting the program coordinators of relevant engineering departments within regional universities to advertise to their student pool. These administrative personnel (who were mostly staff members, rather than faculty) were very effective in not only disseminating the opportunity but also in strongly encouraging their students to apply for and follow through on the REU application process. An added benefit of interacting with these staff members was that they provided almost immediate feedback on how many students would be (and currently were in the process of) applying to the program. Altogether, the above efforts were successful in yielding many more applications than the available participant spots, which turned out to be both a sufficient and diverse applicant pool.

Regarding the application materials, the potential student participants were asked to complete and email fillable word/pdf application forms (questionnaire), curriculum vitae, a personal statement and an unofficial transcript as a single file. Further, they were asked to request 1-2 of their professional contacts to send in a letter of recommendation directly to the program via email, by the (relatively late) deadline of April 30th. Collecting application materials via email was preferred during year-1, in lieu of generating an online fillable form that had to have certain compliance checks. Once all of the participant applications were received, they were screened for eligibility and completeness. A shortlist of these students was securely distributed to the faculty mentors, and their selections/preferences recorded. Selection criteria (which were also communicated in advance to the student applicants) included the following:

- (1) Technical background, attitude, and research aptitude/potential
- (2) Interest in research, higher study, and related STEM careers
- (3) Relevant leadership and extracurricular activities
- (4) Potential to be matched in a vertically-integrated team

Further, students from underserved academic institutions and/or underrepresented groups were especially encouraged to apply. Though the provision existed to conduct brief virtual interviews, this was not needed as there were no significant conflicts in potential participant selections by the faculty mentors, and further the decisions on the student participants were quite clear cut. A decision matrix was then created, distributed among the faculty mentors, and the participants confirmed. Email notifications were then sent out to the ten (10) selected student participants,

with a one (1) week deadline to confirm intent. At the same time, the applicants who were not selected were notified as well via email, taking care to word the notification in a sensitive manner, and encouraging them to apply next year; note that a few students (2-3) who were in the 'buffer' category were not notified at this stage, while waiting for all ten (10) accepted students to confirm intent. This proved useful since not all invited students accepted the offer. Altogether, the recruitment process was successfully completed while taking care to notify all the student participants, whether selected or not, as soon as possible, so they could make appropriate plans.

Once the ten (10) student participants were confirmed, they were officially incorporated into the Texas A&M University system as non-degree-seeking students, but with official student IDs and online system access. Though this involved quite a bit of administrative processing and work behind the scenes, this step was needed so that the incoming REU students had access to all the resources and facilities that regular TAMU student had; this included, but was not limited to: on-campus accommodation, summer campus meal plans, free bus service within the city/campus limits, card access areas, Wi-Fi, libraries, recreation centers, health centers, parking, open access labs, etc. Further, the students were provided concise guidelines and tips on travel to and arrival at TAMU, checking-in to on-campus accommodation, the housekeeping/logistics involved, relevant maps, parking options, finances, activities for the first few days, etc. Such guidelines were provided periodically (as needed) during and after the program, including checking out, travel reimbursements, post-program surveys, follow up and next steps.

Year-1 Site Activities

During the on-site summer period, the major REU activities included a ~40-hour/week hands-on research project, capsulated technical sessions, complementary metrology and NDI labs, tours of major lab facilities, technical seminars, etc. Student-pairs worked closely with their mentor and research group via individual/group meetings. Deliverables included research plan and progress reports, public dissemination through a research paper, poster and presentations, as well as a CV and realization plan tailored to each student's career objectives. Further, the students availed college-sponsored professional networking and development opportunities to develop their soft skills, as part of the Undergraduate Summer Research Grants (USRG) program, culminating in a TAMU-wide research symposium. Figure-1 shows the 2017 REU student cohort, as well as a student pair presenting their poster at the USRG/REU university-wide research symposium.

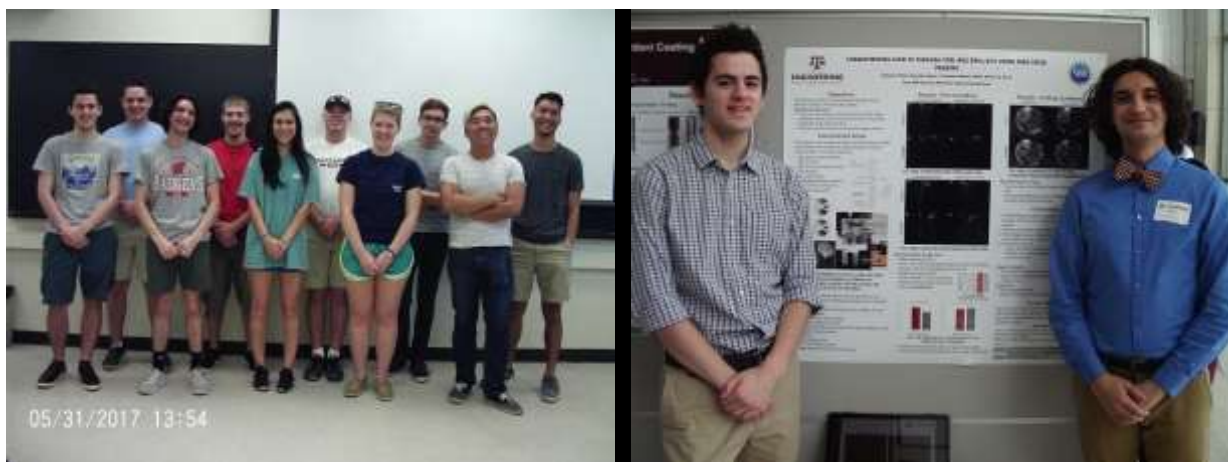


Figure 1: 2017 REU student cohort, and a student pair presenting their poster at the research symposium

For a better snapshot of the REU program schedule, the major pre-, in- and post-program activities and timeline is outlined below in table 1. Note the pre and post-program assessments conducted by internal/external evaluators, as well as the plan for supplementing the on-site experience with a 1-year follow-up, and an extended follow-up to track professional progress.

Table 1: Annual REU site activities including summer plan, pre- and post-program events, and evaluation

<u>MONTH</u>	<u>ANNUAL SCHEDULE OF PRE-PROGRAM EVENTS/ACTIVITIES</u>	
Jan. - Feb.	Initiate contact with institutions. Present/distribute program details. Solicit applications.	
Mar.	Receive applications. Conduct virtual interviews. Select/match REU pairs. Make standby list.	
Apr.	Formal acceptance by REU students. Introduce projects. Knowledge/skill catchup.	
May	Coordinate travel, housing & other amenities. Check-in formalities. Arrive @ TAMU.	
@ TAMU	Pre-program survey (championed by external evaluator).# Debrief. Campus tour.	
<u>(WEEK)</u>	<u>RESEARCH PROJECT EXPERIENCE (VIP TEAMS)</u>	<u>PROFESSIONAL DEVELOPMENT (COE USRG)*</u>
May (Week-1)	Define project objectives, methodology, schedule & outcomes. Specific lab(s) safety.	Welcome breakfast. Orientation. General lab safety training. Welcome Bar-B-Q. Ethics.
Jun. (Week-2)	Research plan due! Overview of metrology/NDI principles, techniques, labs & literature.	<u>GRE workshop</u> : What to expect. <u>Seminar</u> : TAMU early admissions program.
Jun. (Week-3)	Tackle/plan-for research questions & tasks. <u>Train</u> on specific metrology/NDI equipment.	<u>GRE workshop</u> : Maximize your study time. <u>Seminar</u> : Applying to graduate school.
Jun. (Week-4)	Conduct research tasks. Departmental & on-campus (relevant) research center tours.	<u>GRE workshop</u> : Verbal. <u>Seminars</u> : Funding your education; Grad life; Selecting advisors.
Jun. (Week-5)	Conduct research tasks. Prepare progress report & (group) research presentation.	<u>GRE workshop</u> : Quantitative. <u>Seminar</u> : Making the most of your STEM graduate program.
Jul. (Week-6)	Progress report due! Group presentation. Continue research tasks. <u>Do research paper.</u>	<u>GRE workshop</u> : Written/Analytical. <u>Seminars</u> : Graduate school 101; Preparing a CV. BBL%
Jul. (Week-7)	Continue research tasks. Emphasis on correctly interpreting acquitted data.	CV due! Early admissions due. <u>Seminars</u> : Scientific writing; National fellowships. BBL
Jul. (Week-8)	Continue research tasks. Plan/adapt &/or invoke contingency plans to finish on time.	<u>Seminars</u> : Effective poster presentations; Writing abstracts, papers & publishing. BBL
Jul. (Week-9)	Abstract due! Wrap-up research. Prepare paper/presentation/poster. Trial runs. Print.	<u>Seminars</u> : Conflict Resolution; Transition from undergrad to grad school/beyond. BBL
Aug. (Week-10)	Research paper due! Group presentation. Formulate (guided) individual career plans.	Poster due/presentation! <u>TAMU Summer Research Symposium.</u> Awards ceremony.
@ TAMU	Formal survey/interview evaluations (both internal & external). Reflection essay. Dinner.	
Post 1-year	Database & mailing list setup. Scheduled periodic status-update for continued guidance on career objectives (for 1-year). Post opportunities. Strategies to get back on track (if needed).	
Extended	Periodic contact (beyond 1-year). Posting opportunities. Track professional career progress.	
[Fall]	Evaluator report. Discussion & intervention plans. Grad student team-management-training.	

[*TAMU College of Engineering (CoE) Undergraduate Summer Research Grants (USRG) activity]
 [CoE deadline] [#Evaluation activity] [%Brown bag lecture by Institute for Broadening Participation (IBP)]

Altogether, the intended major program activities were accomplished on schedule, in addition to the students gaining professional development skills via the supplementary USRG program. To enhance the knowledge and skill-level of these students in metrology/NDI, the five (5) major intellectual themes, and the specific research projects under these included the following:

1. ***Theme:*** *Comprehensive Forensic Metrology/NDI of Surface & Sub-surface Deterioration*
 - a. ***Project:*** Bio-Inspired Compositional Gradients via LENS Processing for Tailorable Mechanical Responses [12, 13]
 - b. ***Project:*** Texturing of SLM Additive Manufactured Surfaces for Bio-Inspired Control of Friction & Wear [14-16]
2. ***Theme:*** *Non-Destructive Measurement/Tolerancing of Inaccessible Geometries*
 - a. ***Project:*** Selective Surface Modification of Additive Manufactured Parts [17]
 - b. ***Project:*** Tailorable Stiffness & Deformation of 3D-Printed Porous Geometries[18]
3. ***Theme:*** *High-Speed Microscopy/Characterization of the Dynamics of Fluid Flow*
 - a. ***Project:*** Characterizing Flow of Through-Channel MQL Drill Bits Using High Speed Imaging [19]
4. ***Theme:*** *Ultra High-Frequency Bandwidth Measurement of Forces*
 - a. ***Project:*** In-Situ Imaging Observations of Metal Cutting [20, 21]
5. ***Theme:*** *High-Resolution In-situ Scanning/Monitoring of Wellbore Casing Integrity*
 - a. ***Project:*** Drilling Wellbore Pattern Analysis [22]

Project Evaluation (Preliminary Impressions)

Two components/levels of evaluation were conducted as part of this REU site project. First, an external evaluator, by adopting guidelines for good evaluation plans [23], conducted a formative and summative evaluation utilizing the comprehensive, and widely accepted CIPP (Context, Input, Process, Product Evaluation) model [24]. For this, pre- and post- program surveys were developed that were grounded in prior published REU studies and the IRB process; these were used to evaluate whether the site met its recruitment goals, monitor those gains from the program, participant perception of program administration, impact on the career plans of the participants, and also the changes to participant research self-efficacy. The findings from these surveys were collated and discussed. Based on these, certain program changes were suggested.

Additionally, an internal evaluator, served to assess the effectiveness of VIP teams in terms of providing enriching research experiences, as well as resulting student inclination/intent to pursue advanced STEM study. In this capacity, certain research questions were asked that sought to elucidate how the construction of the team affected its performance, how VIPs affect learning experiences differently as compared to traditional single student projects, specific metric-based effectiveness queries, and how it could contribute to the students' inclination to pursue advanced study and STEM careers; these were achieved via evaluation tools such as surveys/interviews.

Though the complete details of these evaluations are not reported in this paper, a qualitative summary follows. The majority (8 of the 10) of the REU students indicated that they would definitely or most likely pursue graduate school, and all of them indicated a definite likelihood of pursuing a career in engineering/science. Additionally, as a result of their REU experience all of the students indicated certain new things (related to the conduction of research) that they did over the summer program duration, besides feeling increased certainty and confidence to complete engineering/research tasks, as compared to when they commenced the REU program. Further, it could be gathered from their comments that most felt more interested in research and graduate school as compared to when they commenced the REU program, besides feeling a new-found confidence in the viability of pursuing a research career.

Future Plans (from Year-2 Onwards)

Based on the lessons learned from the site establishment and activities of year-1, startup motions from year-2 onwards is expected to be much more structured and relaxed, especially since much of the internal paperwork and arrangements are already in place for subsequent years' activities. This includes the procedures for admitting REU students as non-degree seeking students to TAMU, internal approvals, the travel/accommodation/financial logistics and the Institutional Review Board (IRB) approvals. Further, extra effort would be expended to recruit students by contacting appropriate undergraduate program coordinators in universities across the nation. Considering the onsite activities, based on student feedback, some social activities will be implemented, so that the student cohort could develop a sense of comradery among themselves, and develop/maintain a network among themselves, both professional and personal.

Based on the external evaluator's report and comments, an effort will be made to especially solicit students from institutions that are not the standard tier-1 universities; these include community colleges, private colleges, liberal arts colleges, etc. Further, based on some of the pointers obtained from the *NSF Grantees Conference* in 2017, a REU student network group will be initiated on LinkedIn and the professional progress of the students tracked.

Conclusions & Lessons Learned

The purpose of this paper was to outline the quick startup procedures involved in establishing a new NSF REU site, and to detail year-one's major activities, results, impressions, and lessons learned. Due to the expedited timeline involved in setting up the REU site, the time-critical tasks of widely advertising the opportunity to potential student participants and soliciting complete applications from interested undergraduate students were of essence. One resource that proved most effective in disseminating the opportunity and even encouraging local student applicants was the departmental program coordinators at regional universities, who were instrumental in helping to generate a sufficient and diverse applicant pool, besides providing invaluable feedback of applicant numbers to expect from each location. Following the student cohort being selected and the associated administrative processing, the students completed the components of the REU program successfully. In general, the program met its recruitment goals, participants perceived the program positively, and it had an impact on the career plans of the participants in terms of directing them towards advanced study and careers in STEM. Further, the REU student participants expressed their preference in working as a multi-level team towards a research solution, confirming the effectiveness of vertically-integrated project teams. Altogether, the lessons learned from year-1 both in terms of site establishment as well as insights from program evaluations is expected to provide the overall vision needed to provide a fruitful research experience to the future visiting cohort of undergraduates.

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