OULUN AMMATTIKORKEAKOULU

Antti Kyllönen

OHJELMISTORADIOT JA TESTAUSLAITTEISTON VAATIMUSTEN JA TEKNOLOGIOIDEN MÄÄRITTELY

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Opinnäytetyö
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Tieto- ja viestintätekniikan koulutusohjelma
Oulun ammattikorkeakoulu

TIIVISTELMÄ

Oulun ammattikorkeakoulu
Tietotekniikan koulutusohjelma, Laite- ja tuotesuunnittelun suuntautumisvaihtoehto

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Tekijä: Antti Kyllönen
Opinnäytetyön nimi: Ohjelmistoradiot ja testauslaitteiston vaatimusten ja teknologioiden määrittely
Työn ohjaajat: Kari Jyrkkä, Veijo Väisänen
Työn valmistumislukukausi ja -vuosi: Syksy 2017
Sivumäärä: 78

Vuoden 2014 jälkeen Oulun ammattikorkeakoulun tietotekniikan koulutusohjelmassa on ollut valintana tehdä opinnäytetyö kolmessa 5 opintopisteen osassa, joista koostuu yksi koosteopinnäytetyö. Tämä opinnäytetyö koostuu kahdesta eri osasta: ensimmäisestä 5 opintopisteen osuudesta, joka valmistui vuoden 2016 keväällä, ja toisesta, 10 opintopisteen osuudesta, joka valmistui vuoden 2017 kesällä.

Opinnäytetyön ensimmäisessä osassa tehtiin tutkimustyötä ohjelmistoradioista ja niiden toiminnasta. Työn tavoitteena oli selvittää HackRF One -ohjelmistoradion avulla ohjelmistoradioiden käyttöä ja toimintaa sekä niiden sopivuutta opetuskäyttöön.

Opinnäytetyön toinen osa toteutettiin MoveSole Oy:lle, joka on oululainen lääkinnällistä laitetta kehittävä yritys. Työn tavoitteena oli selvittää tuotannossa käytettävän vertikaalista voimaa tuottavan testeri- ja kalibrointityökalun vaatimukset, mahdollisia toteutusteknologioita ja niiden teknologioiden asettamia rajoitteita.

Asiasanat: koosteopinnäyte, ohjelmistoradiot, tuotantotestaus, voimantuotto

SISÄLLYS

1 JOHDANTO

Vuodesta 2014 lähtien Oulun ammattikorkeakoulun tietotekniikan koulutusohjelmassa on ollut kokeilussa koosteopinnäytetyö, jossa perinteinen 15 opintopisteen opinnäytetyö on jaettu kolmeen eri osaan. Työ oli mahdollista suorittaa kahdessa tai kolmessa osassa. Tämän opinnäytetyön ensimmäinen 5 opintopisteen osa valmistui keväällä 2016 ja toinen 10 opintopisteen kokonaisuus valmistui kesällä 2017. Tämän opinnäytetyön kumpikaan osa ei liity toisiinsa, sillä ensimmäinen osa tehtiin toisen lukuvuoden keväällä jostakin mielenkiintoisesta aiheesta, joka oli tullut opintojen aikana vastaan, ja toinen osa tehtiin yritykseen.

Työn ensimmäinen osa keskittyy ohjelmistoradioiden toimintaan, käyttötapoihin ja mahdollisuuksiin. Työn tarkoituksena oli selvittää, soveltuisivatko ohjelmistoradiot hyvin opetuskäyttöön ammattikorkeakoulun tietotekniikan kursseilla. Työssä käytettiin hyötynä HackRF One -ohjelmistoradiota sekä GNU Radio -ohjelmistoa.

Työn toisen osan aihe tuli yritykseltä, jossa suoritin harjoitteluni kesällä 2016 ja jossa olen ollut työntekijänä elokuusta 2016 lähtien. Työn laajuuden takia päätettiin, että toisesta työstä tulisi 10 opintopisteen kokonaisuus. Työn aiheena oli selvittää yrityksen kehittämän laitteen tuotannon testaukseen ja kalibrointiin toteutettavan laitteiston vaatimukset ja tehdä siihen liittyvien teknologioiden alustavaa selvitystä. Kyseessä oli testauslaitteisto, jonka tarkoituksena on generoida vertikaalista voimaa testattavaan laitteeseen.

2 OPINNÄYTETYÖN ENSIMMÄISEN OSAN ESITTELY

Opinnäytetyön ensimmäisen osan (liite 1) aihe tuli ohjaajaltani Kari Jyrkältä, joka halusi tietää, soveltuisivatko ohjelmistoradiot opetuskäyttöön ammattikorkeakoulun tietotekniikan kursseilla mm. signaalinkäsittelyssä. Työn aikana oli tarkoitus selvittää myös, mitkä osat ohjelmistoradioiden järjestelmästä on toteutettu fyysisesti ja mitkä osat on toteutettu ohjelmallisesti, jotta niiden käyttömahdollisuudet ja -rajoitukset selviäisivät.

Työn aikana käytettiin Oulun ammattikorkeakoulun HackRF One -ohjelmistoradiota ja tutkittiin sen avulla ohjelmistoradioiden toimintaa. HackRF Onen lisäksi käytössä oli Linuxilla käytettävä GNU Radio, jolla pystyttiin luomaan sovelluksia, joilla käsiteltiin HackRF Onelta tulevaa digitaalista signaalia.

Opinnäytetyön aikana opin paljon signaalinkäsittelystä ja ohjelmistoradioista ja kiinnostuin varsinkin halvemmista ohjelmistoradioista, joita voi käyttää havaitsemaan ja tarkastelemaan mm. lentokonesignaaleja.

3 OPINNÄYTETYÖN TOISEN OSAN ESITTELY

Opinnäytetyön toisen osan (liite 2) aiheena oli selvittää yritykselle, mitä vaatimuksia yrityksen kehittämä laite ja sen testaus asettavat testauslaitteistolle, jota käytettäisiin kyseisen laitteen tuotannossa. Testauslaitteiston oli tarkoitus tuottaa vertikaalista voimaa yrityksen laitteella oleville antureille, jotta ne voidaan testata ja kalibroida ennen jakeluun siirtymistä. Työssä käydään läpi sensori, jota testauslaitteistolla on tarkoitus testata, testattavan tuotteen asettamat vaatimukset, testauslaitteiston teknologiavaihtoehtoja ja siinä mahdollisesti käytettävän voimanmittausanturin ominaisuuksia.

Työ sisälsi teknologioiden taustatutkintaa, erilaisten testien toteuttamista ja testitulosten tulkintaa sekä kuvausta. Työssä käytiin laajalti läpi testauslaitteiston sähköisiä ja mekaanisia ominaisuuksia, ohjelmistollisia tarpeita sekä testattavan laitteen ominaisuuksia. Työssä täytyi ottaa myös huomioon, että testattavana laitteena on lääkinnällinen laite, joten testauksen ja kalibroinnin tärkeys oli korostetussa asemassa. Työ on kirjoitettu englannin kielellä, koska sen on tarkoitus olla osa yrityksen sisäistä dokumentaatiota, joka on kaikki kirjoitettu englannin kielellä.

Työtä toteutettaessa opin paljon yrityksen sisällä tehtävästä dokumentaatiosta, tieteellisen dokumentoinnin tarkkuudesta ja antureista, joita MoveSolen tuotteessa käytetään. Lopputuloksena työstä saatiin kattava vaatimuslista, jonka pohjalta testauslaitteistoa voi alkaa suunnitella.

4 YHTEENVETO

Opinnäytetyö suoritettiin kahdessa osassa, joista ensimmäinen osa oli laajuudeltaan 5 opintopistettä ja toinen 10 opintopistettä. Kahdessa eri osassa tekeminen tuntui sujuvalta, sillä työmäärän sai jaettua niin, että koosteopinnäytetyö valmistui nopeammin kuin jos olisin tehnyt opinnäytetyön perinteisellä tavalla.

Koosteopinnäytetyön kaksi osaa eroavat täysin toisistaan, mutta ensimmäinen osa kuitenkin liittyy suuntautumisvaihtoehtooni enemmän kuin toinen osa. Siinä pääsi tutustumaan signaalinkäsittelyyn ja langattomaan tiedonsiirtoon tarkemmin kuin mitä olin siihen mennessä tutustunut. Työstä selvisi, että ohjelmistoradiot ovat mainio apuväline opetuksessa.

Työn toisen osan tein yritykselle, jossa olin ollut työntekijänä jo 9 kuukautta, joten pääsin tekemään jotain, joka oli oikeasti mielenkiintoista ja merkityksellistä. Työ opetti minulle myös paljon yrityksen kehittämässä tuotteessa käytettävistä antureista. Antureiden parissa työskentely oli erittäin mielenkiintoista, sillä antureiden käsittely ei kuulunut aiempaan työkuvaani. Pääsen jatkamaan opinnäytetyössä käsiteltyjä asioita ja testauslaitteiston suunnittelua yrityksessä jatkossakin, mikä toi työhön lisämerkitystä.

LIITTEET

Liite 1 Ohjelmistoradiot

Liite 2 StepLab calibration and test tool specification

LIITE 1

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OHJELMISTORADIOT

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SISÄLLYS

1 JOHDANTO

Tämä työ on kolmiosaisen opinnäytetyön 1. osa ja se sijoittuu toisen opiskeluvuoden keväälle viiden opintopisteen osuutena. Ensimmäisen osan tarkoituksena on laatia syventävä selvitys jostakin mielenkiintoisesta aiheesta, joka on tullut opintojen aikana vastaan.

Valitsin aiheekseni ohjelmistoradiot, koska uskoin että pystyisin tämän aiheen kautta oppimaan lisää langattomasta tiedonsiirrosta, jonka koin olevan heikkouteni. Aiheen valintaan vaikutti myös se, että pystyin samanaikaisesti testaamaan koululta löytyvää HackRF One -ohjelmistoradiota.

Ohjelmistoradioiden harrastajien määrä on lisääntymässä, kun tekniikan kehittymisen myötä pystytään tuottamaan halvempia ja helpommin saatavilla olevia laitteita. Näin voidaan myös mahdollistaa ohjelmistoradioiden käyttö tietotekniikan opiskeluympäristöissä soveltamalla ohjelmistoradioita esimerkiksi niin, että sitä voitaisiin käyttää oskilloskooppina tai funktiogeneraattorina.

Opinnäytetyön tavoitteena on selvittää ohjelmistoradioiden toiminta, sekä niiden käyttötapoja ja mahdollisuuksia. Tarkoituksena on myös selvittää, mitkä osat ohjelmistoradioiden järjestelmästä on toteutettu fyysisesti laitteessa ja mitkä ohjelmiston puolella HackRF One -ohjelmistoradiota tutkimalla. Tarkoituksena olisi myös löytää vaihtoehtoinen laite vain signaalien kaappaamiseen (RTL-ohjelmistoradio) ja selvittää, miten ohjelmistoradiot sopisivat opetuskäyttöön.

2 OHJELMISTORADIO

Ohjelmistoradio on radiokommunikaatiolaite, jossa osa radion fyysisestä laitteistosta on toteutettu ohjelmistossa. Ohjelmistossa voidaan muokata laitteiston ominaisuuksia käyttäjän tarpeen mukaan. Ohjelmistoradiolla voidaan sekä lähettää että vastaanottaa monien eri radioprotokollien signaaleja. Käytännössä yksi ohjelmistoradio kykenee toimimaan oikeastaan minkä tahansa langattoman protokollan kanssa (mm. Bluetooth, FM Radio, ZigBee, matkapuhelinverkko). Protokollapinon jakaminen laitteiston ja ohjelmiston kesken ohjelmistoradiolla riippuu paljolti käytettävästä laitteistosta ja protokollasta, kuitenkin niin että osa laitteiston protokollapinosta siirtyy ohjelmistoradioissa ohjelmiston puolelle.

Ohjelmistoradion suurin ero tavallisiin laitteistopohjaisiin radiolaitteisiin on se, että sen järjestelmä ei ole täysin laitteistopohjainen. Osa tavallisen radiolaitteen komponenteista on toteutettu tai niille annetaan parametreja erillisessä tietokoneohjelmassa, joka suoritetaan yleiskäyttöisessä PC-laitteistossa.

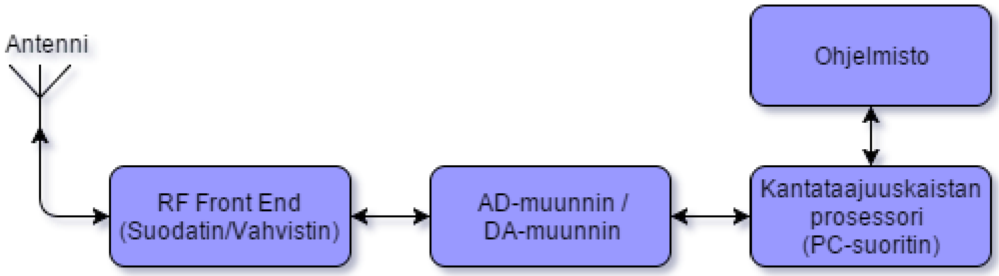
2.1 Ohjelmistoradion toiminta

Nykyään suurin osa ohjelmistoradioista yhdistetään tietokoneeseen USB-portin kautta, mutta osa, varsinkin laadukkaammat ja kalliimmat laitteet toimivat joko tietokoneen Ethernet-portin tai PCIe-portin kautta. Ennen teknologian kehittymistä nykyajan tasolle ohjelmistoradiot joutuivat käyttämään äänikorttia yhdistääkseen itsensä tietokoneeseen sisäisen analogia-digitaalimuuntimen puutteen takia.

Ohjelmistoradioiden ohjaamiseen käytettäviä ohjelmia on olemassa kymmeniä, ellei satoja. Kaikista käytetyin niistä on kuitenkin ilmainen SDR#, jota on muihin ohjelmiin verrattuna yksinkertaisin käyttää. (1.)

Esimerkiksi signaaleja vastaanottaessa ohjelmistoradion laitteisto säätää vastaanotettavan signaalin kantataajuudelle, jossa sitä voidaan käsitellä paremmin tietokoneella (paitsi jos vastaanotettava signaali on jo valmiiksi kantataajuudella). Tämä toteutetaan muokkaamalla ohjelmistoradiolaitteen sisällä oleville komponenteille annettavia arvoja, mm. sekoittimet, vahvistimet ja suodattimet.

Arvot annetaan laitteen sisällä olevalle prosessorille, joka säätää muut komponentit niiden mukaisesti. Loput ohjelmistoradion toiminnoista toteutetaan täysin ohjelmiston sisällä. Lohkokaavio toiminnasta on kuvattu kuvassa 1.



KUVA 1 Ohjelmistoradion toiminnan lohkokaavio

Käytännössä kaikki laitteen komponentit paitsi antenni ja AD/DA-muunnin voitaisiin toteuttaa ohjelmistossa. Tällaista laitetta kutsuttaisiin ideaaliseksi ohjelmistoradioksi.

2.2 Radiotyypit

Ohjelmistoradioyhteisö on epävirallisesti määritellyt eri radiotyypit viiteen eri luokkaan seuraavasti: (2, s. 2, 3.)

0. Laitteistoradio (HW): täysin laitteistoon pohjautuva radio, jota ei voi muunnella ohjelmistoilla.
1. Ohjelmistokontrolloitu radio (SCR): rajattu määrä radion toiminnoista on kontrolloitavissa ohjelmiston kautta, esimerkiksi tehotasot ja yhteydet.
2. Ohjelmistomääritelty radio (SDR): merkittävä osa radion toiminnoista on mahdollista määrittää ohjelmiston kautta. Ohjelmistomääritellyn ohjelmistoradion muokattaviin parametreihin kuuluvat lisäksi esimerkiksi taajuus, modulaatio, turvallisuus ja aaltomuodon luonti ja tunnistus.
3. Ideaalinen ohjelmistoradio (ISR): vain antennin lähistöllä sijaitsevat elementit jäävät käyttäjän muokkaamattomiksi. Ideaalisessa ohjelmistoradiossa antennin ja prosessorin välillä olisi vain AD- tai DA-muunnin ja vahvistin. Teknologiarajoitteiden takia ideaalista ohjelmistoradiota ei olla vielä pystytty valmistamaan.

4. Ultimaattinen ohjelmistoradio (USR): ultimaattinen ohjelmistoradio on ideaalisesta ohjelmistoradiosta seuraava askel. Sillä on täysi ohjelmoitavuus ja se kykenee laajan alueen toimintoihin ja vastaanottamaan ja lähettämään eri taajuuksia yhtäaikaisesti. Tämän toteuttaminen olisi erittäin hyödyllistä matkapuhelimille ja tukiasemille.

3 HACKRF ONE

HackRF One on täysin avoimen lähdekoodin ohjelmistoradio-oheislaite, jota voi käyttää USB-oheislaitteena PC:n kanssa tai omana laitteenaan. HackRF One esitetty kuvassa 2.

KUVA 2 HackRF One (5)

HackRF One kykenee vastaanottamaan ja lähettämään signaaleja 1 MHz – 6 GHz:n taajuuksilla ja se on yhteensopiva GNU Radio- ja SDR#-ohjelmistojen kanssa. HackRF One on vuorosuuntainen (half-duplex) ohjelmistoradio, joten se ei kykene lähettämään ja vastaanottamaan samanaikaisesti.

HackRF Onen olemassaolo mahdollistettiin Kickstarter-joukkorahoituspalvelun kautta, jossa se ylitti rahoitustavoitteensa yli seitsemänkertaisesti.

3.1 Laitteiston sisältö

Merkittävimmät osat HackRF Onen laitteistosta: (13)

- MAX2837 lähetin-vastaanotin
- MAX5864 AD-/DA-muunnin
- Si5351 CMOS-kellogeneraattori
- CoolRunner II kompleksi ohjelmoitava logiikkalaite
- LPC43xx ARM Cortex-M4 mikrokontrolleri
- RFFC5072 mikseri/syntetisaattori

Tämän laitteiston avulla voidaan vastaanottaa ja lähettää HackRF Onen rajoitteiden sisällä olevia signaaleja käyttäen jotakin ohjelmistoa apuna.

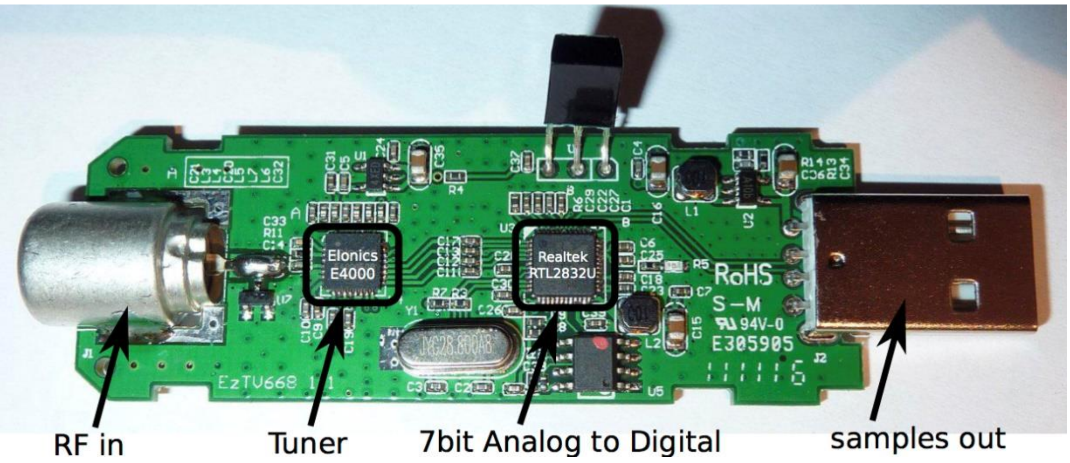
3.2 Ohjelmisto

Suurin osa ohjelmistoradio-ohjelmistoista tukee HackRF Onea. HackRF Onelle löytyy ajurit ja niiden asennusohjeet verkosta Windowsille, OS X:lle ja Ubuntu-, Arch-, Gentoo- ja muutamille muille Linux-jakeluille. (6,7.)

4 RTL2832U-POHJAISET OHJELMISTORADIOT

RTL2832U on Realtekin valmistama demodulaattori, jota käytetään ensisijaisesti maanpäällisten digitaalitelevisiokanavien lähetysten vastaanottamiseen. Radioharrastajat ovat ottaneet RTL2832U-pohjaiset USB-digitaaliviirittimet käyttöönsä saadakseen halvan langattoman signaalin vastaanottolaitteen. Näitä kutsutaan RTL-ohjelmistoradioiksi.

RTL2832U-pohjainen digitaaliviritin kykenee signaalien vastaanottamiseen kuten tavalliset ohjelmistoradiotkin, mutta sillä ei voida lähettää tai luoda signaaleja. RTL-ohjelmistoradion vahvuutena on sen halpa hinta ja saatavuus. Ohjelmistoradiot, joilla voi lähettää ja vastaanottaa, voivat maksaa satoja euroja, kun taas RTL-ohjelmistoradioiden hinnat ovat kymmeniä euroja (9). RTL-ohjelmistoradioiden heikkoutena on niiden suppeampi taajuusalue ja pienempi taajuuskaista, jotka myös vaihtelevat laitteittain. Kuvassa 2 esitetty RTL2382U-sirua käyttävän USB-digivirittimen sisältö.



KUVA 3 Elonics 4000-viritintä hyödyntävä RTL-pohjainen USB-digitaaliviritin (11)

RTL2832U:lle ei löydy julkisesti esillä olevaa datalehteä, koska sitä käyttävien tuotteiden valmistajat ovat tehneet salassapitosopimuksen Realtekin kanssa valmistaakseen tuotetta (4). Tämän takia yksityinen harrastelija ei voi rakentaa omaa RTL2832U-pohjaista laitettaan, vaan joudutaan käyttämään tiettyjen valmistajien myymiä USB-dongleja. USB-donglen hinta riippuu paljolti siinä käytettävästä virittimestä, yleisimmin hinta on luokkaa 10 - 40 €, niin että virittimen taajuusalue ja laatu vaikuttavat donglen lopulliseen hintaan eniten.

RTL-ohjelmistoradioita tukevia ohjelmistoja on suuri määrä. Suurin osa yleisimmistä ohjelmistoradioita tukevista ohjelmistoista tukee myös RTL-ohjelmistoradioita. (10.)

4.1 RTL-ohjelmistoradion toiminta

RTL2832U:n ulostulo on 8-bittistä I/Q-dataa ja sen teoreettinen maksiminäytteenottotaajuus on 3.2 MS/s. Korkein testattu näytteenottotaajuus, jolla ei menetetä näytteitä, on 2.56 MS/s. Taajuusalue riippuu hyvin paljolti käytetystä virittimestä ja on huomattu, että Elonics E4000-viritintä käyttävillä dongleilla on laajin taajuusalue (11).

TAULUKKO 1 RTL2832U-dongleissa käytettävien virittimien taajuusalueita (11)

Viritin	**Taajuusalue**
Elonics E4000	52 - 2200 MHz (~1100 MHz – 1250 MHz alueella väli)
Rafael Micro R820T	24 - 1766 MHz
Rafael Micro R828D	24 - 1766 MHz
Fitipower FC0013	22 - 1100 MHz
Fitipower FC0012	22 - 948.6 MHz
FCI FC2580	146 - 308 MHz ja 438 - 924 MHz

RTL-ohjelmistoradiossa tarvitaan jokin digitaalisesti ohjattava viritin, joka voisi olla esimerkiksi yksi taulukko 2:ssa mainituista virittimistä. RTL-ohjelmistoradiossa viritin valitsee taajuuskaistan kohdetaajuuden ympärille ja demoduloi sen kantataajuuskaistalle. RTL2832U toimii ohjelmistoradiossa AD-muuntimena, joka ottaa näytteitä kantataajuuskaistan signaalista ja vie näytteet USB-portin kautta tietokoneelle.

4.2 RTL-ohjelmistoradion käyttö

RTL-ohjelmistoradiota käytetään yleisimmin radioharrastelijan ensimmäisenä ohjelmistoradiona. Se on suosittu aloittelijoiden keskuudessa helpon saatavuutensa ja halvan hintansa takia, sekä siksi, että sen käyttöön löytyy erittäin laajalti yhteensopivia ohjelmistoja, ajureita, ohjeita ja vinkkejä. RTL-ohjelmistoradiolla on pystytty vastaanottamaan sääsatelliittien signaaleja ja jopa ISS:n (International Space Station) avaruuskävelyn kommunikointia ja SSTV-lähetyksiä käyttämällä suurta antennia ja dekoodaamalla vastaanotettu signaali. (12.)

Internet on täynnä eri skriptejä ja ohjelmia, jotka on suunniteltu dekoodaamaan tiettyjä signaaleja, joten RTL-ohjelmistoradiolla on hyvin laajat mahdollisuudet päästä testaamaan hakkerointia. RTL-ohjelmistoradio voisi soveltua myös opetuskäyttöön halvan hintansa, saatavuutensa ja helppokäyttöisyytensä johdosta.

5 OHJELMISTOT

Ohjelmistoradioiden käyttämät ohjelmat jaetaan kahteen luokkaan – yleiskäyttöön tarkoitettuihin ohjelmiin ja tutkimukseen tarkoitettuihin ohjelmiin. Yleiskäyttöön tarkoitetut ohjelmat ovat lähinnä amatöörikäyttöön ja niillä mahdollistetaan helppokäyttöisyys graafista käyttöliittymää käyttäen. Tutkimuskäyttöön tarkoitetut ohjelmat ovat hieman monimutkaisempia käyttää ja vaativat oikeata tietoa radioista ja radioprotokollista. Ne ovat lähinnä tutkimus- ja opetuskäytössä. Näiden lisäksi käytetään myös joitakin ohjelmia, joita ei ole luotu ohjelmistoradiokäyttöön, mutta niitä voidaan hyödyntää ohjelmistoradion kanssa muun muassa vastaanotetun datan dekookaukseen. Esimerkiksi WxtoIMG mahdollistaa NOAA-sääsatelliittien datan dekookauksen.

5.1 Yleiskäyttöön tarkoitetut ohjelmistot

Yleiskäyttöön tarkoitettuja ohjelmistoja löytyy varmasti jokaiselle sopivia. Tarjolla on avoimen lähdekoodin, maksullisia ja maksuttomia, eri käyttöjärjestelmillä toimivia ja eri ominaisuuksia sisältäviä ohjelmia.

Tunnetuin yleiskäyttöön tarkoitettu ohjelma on SDR#. Se on luotu Windows-käyttöjärjestelmillä toimivaksi, se on ilmainen ja helppo oppia käyttämään. SDR#:n käyttöön löytyy lukuisia oppaita joten uuden käyttäjän on hyvä lähteä ohjelmistoradioiden maailmaan SDR#:n avulla. SDR#:lle löytyy myös laaja valikoima käyttäjien luomia lisäosia, jotka tekevät ohjelmistosta käytetyimmän ja laajentavat sen käyttömahdollisuuksia huomattavasti. (14.)

GQRX on ilmainen, Mac- ja Linux-alustoilla toimiva ohjelma, joka vastaa helppokäyttöisyydeltään ja ominaisuuksiltaan SDR#:a. Sillä ei kuitenkaan ole niin laajaa määrää lisäosia, mutta se sopii hyvin aloittelevalle käyttäjälle jolla ei ole mahdollisuutta Windows-työympäristön käyttöön.

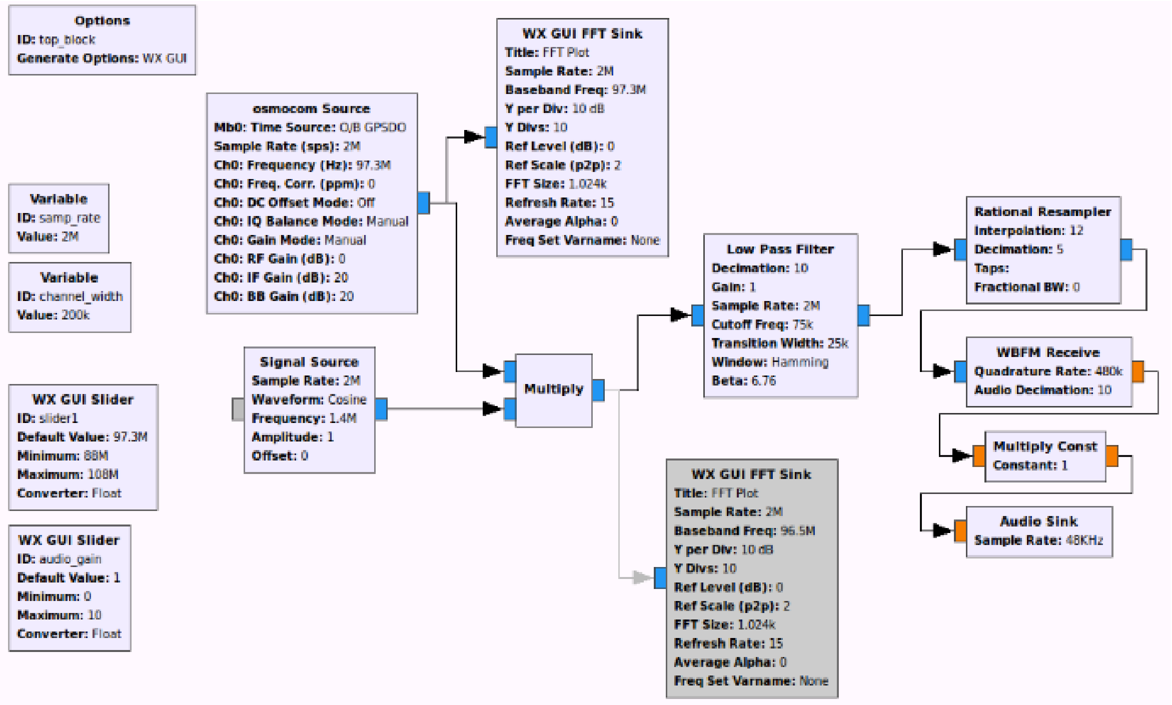
Linrad on ilmainen Windows-, Linux- ja Mac-alustoilla toimiva ohjelmistoradio-ohjelma, joka on luotu edistyneemmille käyttäjille. Se sopii erittäin hyvin yhteen

E4000-mallisen RTL-ohjelmistoradion kanssa. Linradissa on monia edistyneempiä ominaisuuksia, joita ei löydy muista ohjelmistoradio-ohjelmista, kuten erittäin tehokas kohinanpoistaja ja monikanavaisen lähetyksen ulostulotuki.

SDR Touch on ensimmäinen Android-pohjainen RTL-ohjelmistoradio-ohjelma, joka tukee Android 4.0 ja uudempia Android-käyttöjärjestelmiä. SDR Touch sisältää monia perusominaisuuksia, joilla päästään RTL-ohjelmistoradioiden maailmaan. SDR Touchista on tarjolla ilmainen kokeiluversio, mutta täydestä versiosta pitääkin sitten maksaa. SDR Touchia (tai mitä tahansa muuta mobiililaitteella toimivaa RTL-ohjelmistoradio-ohjelmaa) käytettäessä tarvitsee kuitenkin USB On-The-Go -kaapelin, jotta voidaan yhdistää RTL-ohjelmistoradio mobiililaitteeseen. (1.)

5.2 Tutkimuskäyttöön tarkoitetut ohjelmistot

Yleisimmin käytetty tutkimuskäyttöön tarkoitettu ohjelma on Linuxilla käytettävä GNU Radio. GNU Radio on ilmainen, avoimen lähdekoodin digitaalinen signaalinkäsittelyohjelmistopaketti. Sillä voidaan luoda sovelluksia, joilla voidaan vastaanottaa dataa digitaalisessa muodossa ohjelmistoradiolta tai vastaavasti lähettää digitaalista dataa ohjelmistoradiolle. GNU Radio sisältää lukuisia työkaluja, joita voidaan käyttää ohjelmistoradiosovelluksen luontiin. Esimerkiksi GNU Radio Companion, jolla käyttäjä voi luoda lohkokaavion, jonka pohjalta ohjelma kirjoittaa Python-koodia ohjelmistoradiosovellukseen.



Options
ID: top_block
Generate Options: WX GUI

Variable
ID: samp_rate
Value: 2M

Variable
ID: channel_width
Value: 200k

WX GUI Slider
ID: slider1
Default Value: 97.3M
Minimum: 88M
Maximum: 108M
Converter: Float

WX GUI Slider
ID: audio_gain
Default Value: 1
Minimum: 0
Maximum: 10
Converter: Float

osmocom Source
Mb0: Time Source: O/B GPSDO
Sample Rate (sps): 2M
Ch0: Frequency (Hz): 97.3M
Ch0: Freq. Corr. (ppm): 0
Ch0: DC Offset Mode: Off
Ch0: IQ Balance Mode: Manual
Ch0: Gain Mode: Manual
Ch0: RF Gain (dB): 0
Ch0: IF Gain (dB): 20
Ch0: BB Gain (dB): 20

Signal Source
Sample Rate: 2M
Waveform: Cosine
Frequency: 1.4M
Amplitude: 1
Offset: 0

WX GUI FFT Sink
Title: FFT Plot
Sample Rate: 2M
Baseband Freq: 97.3M
Y per Div: 10 dB
Y Divs: 10
Ref Level (dB): 0
Ref Scale (p2p): 2
FFT Size: 1.024k
Refresh Rate: 15
Average Alpha: 0
Freq Set Varname: None

Multiply

Low Pass Filter
Decimation: 10
Gain: 1
Sample Rate: 2M
Cutoff Freq: 75k
Transition Width: 25k
Window: Hamming
Beta: 6.76

WX GUI FFT Sink
Title: FFT Plot
Sample Rate: 2M
Baseband Freq: 96.5M
Y per Div: 10 dB
Y Divs: 10
Ref Level (dB): 0
Ref Scale (p2p): 2
FFT Size: 1.024k
Refresh Rate: 15
Average Alpha: 0
Freq Set Varname: None

Rational Resampler
Interpolation: 12
Decimation: 5
Taps:
Fractional BW: 0

WBFM Receive
Quadrature Rate: 480k
Audio Decimation: 10

Multiply Const
Constant: 1

Audio Sink
Sample Rate: 48KHz

Kuva 4 GNU Radio Companionissa lohkokaavioilla rakennettu FM-radiovastaanotin

GNU Radion pohjalta on rakennettu lukuisia ohjelmistoradioprojekteissa käytettäviä ohjelmistoja, kuten web-pohjainen digitaalinen signaalinkäsittelyohjelma ShinySDR ja eri dekooderiohjelmia. Osa GNU Radion toiminnoista jää joko käyttäjän itsensä ohjelmoitavaksi tai liitännäisillä toteutettavaksi, mutta peruskäyttäjän ei välttämättä tarvitse näitä ominaisuuksia.

Monet pitävät GNU Radiota amatööriprojektina ja ohjelmistona, jota käyttäisi prototyyppeihin, muttei koskaan oikeisiin sovelluksiin. Oikeisiin sovelluksiin voitaisiin käyttää esimerkiksi Redhawkia (8). Redhawk on hyvin samanlainen digitaalinen signaalinkäsittelypaketti kuin GNU Radio, sen kohdeyleisö on vain hieman ammattimaisempi.

Opetuskäyttöön sopiva, Windows-pohjainen ja ilmainen SDRLab hyödyntää RTL2832U-pohjaisia ja NI USRP-2922 -ohjelmistoradioita signaalin vastaanottamiseen ja käsittelyyn. SDRLabin heikkoutena on puutteet ominaisuuksissa.

Myös MATLABia voidaan käyttää RTL-ohjelmistoradion signaalin vastaanottamiseen ja käsittelyyn.

6 YHTEENVETO

Opinnäytetyössä perehdyttiin pintapuolisesti ohjelmistoradioihin ja selvitettiin, millaisia mahdollisuuksia ohjelmistoradioilla on. Pääsin myös kokeilemaan HackRF One -ohjelmistoradiota käytännössä ja perehtymään asiaan tarkemmin siltäkin kantilta. Halusin myös selvittää ohjelmistoradioiden mahdollisuuksista opetuskäytössä, varsinkin oman alani opetuksessa.

Opinnäytetyötä tehdessäni selvisi, että käytännöllisin laite- ja ohjelmistokombinaatio opetuskäyttöön olisi joku RTL-ohjelmistoradio ja GNU Radio Companion. RTL-ohjelmistoradion käyttö olisi oppilaitokselle kohtuullisen halpaa. Yksi pienikokoinen opiskelijaryhmä voisi pärjätä yhdellä n. 20 euron hintaisella RTL-ohjelmistoradiolla ja ilmaisella GNU Radio Companionilla. Pääasiassa opetuskäytössä ohjelmistoradiolta vaadittaisiin vain vastaanottamista, joten RTL-ohjelmistoradiolla riittäisi tähän hyvin. Jos kuitenkin tarvitaan myös signaalin lähettämistä, HackRF One voisi olla siihen sopiva vaihtoehto hintansa ja helposti saatavilla olevien ohjeiden määrän takia.

Esimerkiksi FM-radiovastaanottimen luominen GNU Radio Companionilla auttaisi opiskelijaa ymmärtämään signaalin vastaanottoon tarvittavien osien tarkoitusta ja merkitystä, kun joutuu itse lohkokaaviomallilla rakentamaan vastaanottimen alusta loppuun. Myös vastaanotetun signaalin käsittely onnistuisi RTL-ohjelmistoradion ja jonkin ohjelman avulla. Voitaisiin esimerkiksi antaa opiskelijalle tehtäväksi vastaanottaa joku tietty signaali, joka pitää sitten osata dekoodata.

Tällä hetkellä ongelmana GNU Radio Companionin käytöllä on käyttöjärjestelmärajoittuneisuus, sillä se toimii vain Linux-käyttöjärjestelmillä. Windows kuitenkin toteuttaa kesän 2016 aikana Windows 10 -alustoille natiivin bash-komentorivin, joten jatkossa Windows 10 -alustoille voidaan myös asentaa Linuxille suunnattuja ohjelmia. (15.)

Opinnäytetyön kirjoittamisen aikana olen oppinut paljon uutta ja vahvistanut vanhaa tietoa ohjelmistoradioista, langattomasta tiedonsiirrosta ja eri tiedonsiirtoprotokollista.

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STEPLAB CALIBRATION & TEST TOOL SPECIFICATION

STEPLAB CALIBRATION & TEST TOOL SPECIFICATION

Antti Kyllönen
Bachelor’s Thesis
Spring 2017
Information Technology
Oulu University of Applied Sciences

ABSTRACT

Oulu University of Applied Sciences
Information Technology, Product & Device Design

Author: Antti Kyllönen
Title of the bachelor’s thesis: StepLab Calibration & Test Tool Specification
Supervisors: Veijo Väisänen
Term and year of completion: Spring 2017 Number of pages: 50

The objective of this thesis was to research and provide the requirements for a test and calibration tool which will be implemented for the production testing and calibration of a medical measuring device. The device uses electromechanical sensors, which measure force. This means that the main functionality of the test and calibration tool is to apply force vertically by compressing the sensors.

The commissioner requested for a thorough consideration of what requirements their product imposes on the test and calibration tool that it will be tested and calibrated with. In addition to providing the requirements of the tool, technology research and benchmarking for the major components of the test tool were requested.

The requirements were researched by studying the functionality of the product and the sensors in it. This was achieved by conducting several types of tests, and by discussing the pre-requirements of the test and calibration tool with the commissioner of the thesis. Once the requirements were thoroughly researched and provided, a technology research on actuation methods and reference sensors was conducted alongside with some benchmarking of components that may end up in the finished tool.

Keywords: production tester, electromechanical sensor, linear force actuators

PREFACE

This thesis was commissioned by MoveSole Oy and it was carried out during the summer of 2017. It is the second part of a two-part thesis and it is a 10 course credit portion of the 15 course credit thesis.

I would like to thank Vesa Kajanus of MoveSole Oy for acting as my supervisor during this thesis, and giving me guidance and tips when necessary. I would also like to thank MoveSole Oy for allowing me to join their ranks early on in my studies. Having worked as part of the development team for StepLab for almost a year before starting this thesis gave me a great overview of the product, which helped me to understand the purpose of the calibration & test tool and its requirements better from the beginning.

This thesis is a shortened version of the original document which is stored alongside with other StepLab related documentation. Some parts of the original documentation were not to be shared publicly and they were either omitted from the final report or explained with similar methods.

Oulu, 16.08.2017
Antti Kyllönen

CONTENTS

VOCABULARY

BLE	Bluetooth Low Energy (Bluetooth 4)
Coated insole	Sensor insole with protective coating
DUT	Device Under Test
Plain insole	Uncoated sensor insole
Plain sensor	Electromechanical sensor used in StepLab products
R&D	Research and Development
Smart insole	Coated insole with electronics components and software
SoC	System-on-chip

1 INTRODUCTION

This thesis was commissioned by Movesole Oy. Movesole is a start-up company, located in Oulu, which is developing a medical device system called StepLab. The company was established in 2014 and it has focused on developing this product since its inception.

StepLab is a product which consists of one or more smart insole(s), a smart device with the StepLab Android application installed on it and accessories. The StepLab Android application and smart insole are shown in figure 1. StepLab is used by medical professionals to measure instant force and timing information from selected locations under the feet of a patient. The smart insoles communicate with the smart device and the measured data is portrayed on the screen of the smart device. This makes it a medical measuring device system, which means that the sensors in the smart insoles need to be calibrated accurately to achieve reliable output data and thus patient security.

FIGURE 1 StepLab system components

The object of this thesis was to provide requirement specifications for a calibration & test tool which will be used to test and calibrate the smart insoles and to research viable components for the tool so that MoveSole can make a confident decision on the direction of the calibration & test tool design. This thesis will not include any decision making on the technology that the company will move forward with. The test tool should fit the requirements of the plain sensors, intended use, production, and R&D of the smart insole, which will be researched and documented in this thesis.

The StepLab calibration & test tool is a test harness which consists of three parts – a test system control device, reference force test equipment and a DUT (device under test) as shown in figure 2. The test system control device will act as a central control device of the test harness and communication interface between the DUT and the reference force test equipment. The reference force test equipment is a tool which will apply dynamic vertical force to the DUT with one of the actuating technologies studied in this thesis. The DUT could be one of three different devices, each being a part of the production chain of StepLab smart insoles.

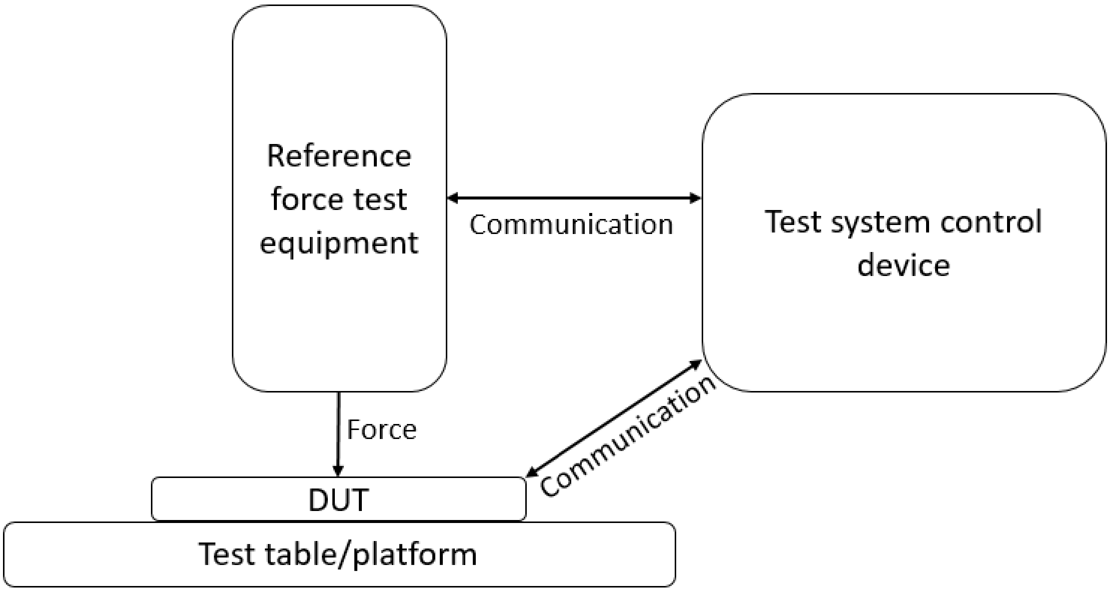

FIGURE 2. StepLab test harness

2 SENSOR TECHNOLOGY

2.1 Smart insole assembly and test phases

Because StepLab is a medical device system, which can be used as a tool to resolve ways to help a patient, the data it portrays needs to be accurate to preserve patient safety. The test harness will be used to make sure that the plain sensors that are used in a StepLab smart insole will be functional, accurate and within acceptable limits of sensitivity difference.

A smart insole needs to be tested in three phases to ensure that the final product is functional and that the calibration is done correctly. The first phase is plain sensor testing where the plain sensor, which is cut to different shapes will be tested. The second phase is the testing of plain insoles which contain the plain sensors and conductive wiring to pin heads. The third test phase is the testing of coated insoles. The coated insoles are the final form of the insole component of the smart insole, which is essentially a plain insole coated with a protective material designed to protect the plain sensor and to make the smart insole usable in a shoe. The coated insole is shown in figure 3, where its maximum dimensions can be seen.

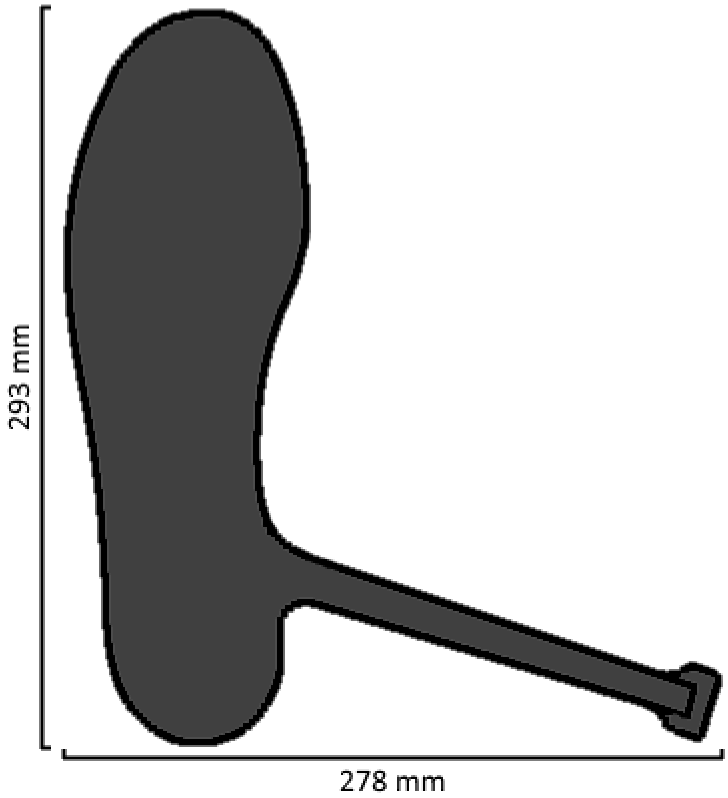

FIGURE 3. Coated insole structure. The dimensions were measured from a European shoe size 46 smart insole.

The tests will be performed using the test harness that has been researched in this thesis. The reference force test equipment in the test harness will apply vertical force to the DUT with a test head which has elastic rubber material on the end that presses the DUT.

The sensitivity of the sensors in the plain insole and coated insole need to be tested after they have been assembled to make sure that they are still functional and operate correctly at the required ranges. After completing the tests on a coated insole, each sensor in it needs to be calibrated separately to ensure the quality of the measurement. The sensor is the origin of the data, therefore any inaccuracy in the sensor is amplified in the data that is visualized to the user. Several separate phases of data analysis and processing happen between the measurement from the sensor and the smart device interface of the end user, which cause even the smallest deviations in plain sensor sensitivity to distort the data and render inaccurate and unreliable readings.

2.2 Plain sensor

The sensors that will be calibrated with the StepLab calibration & test tool are sensors that measure dynamic force applied to the sensor. The primary component of the sensor is an electromechanical film **reading** is essentially a polypropylene sheet with electrically charged air void bubbles inside (1, p. 629). The cross-section structure of the electromechanical film with metal electrodes can be seen in figure 4.

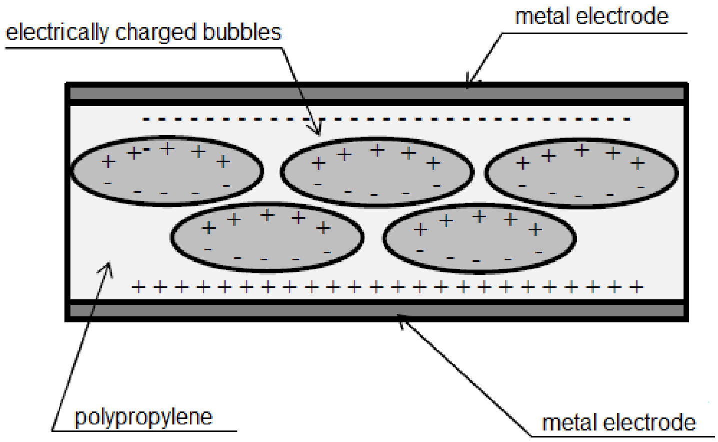

FIGURE 4. Cross section of the electromechanical film. StepLab plain sensors do not include the metal electrodes (2, p. 11).

The electrically charged, air filled bubbles induce a change of charge on the metal electrodes when pressed by an external force. By measuring the charge of the electrodes on the electromechanical film, an analog signal, which represents change of force, can be read. An example of the operating range, sensitivity and other properties of electromechanical film manufactured by Emfit can be seen in table 1.

TABLE 1. Properties of electromechanical film by Emfit (3.).

Property	Value	Unit	Tolerance
Thickness	0,08	mm	±5%
Sensitivity without preaging	250-400	pC/N	±20%
Capacitance at 1-150 kHz	22	pF/cm^2	±5%
Operating force range	< 300	N/cm^2	
Operating temperature	-20 … +70	°C	
Storage temperature	-40 … +50	°C	

2.3 Plain insole

To use the plain sensor as a part of a smart insole, it needs electrodes and other layering on it. The plain insole is constructed from a plain sensor, electrodes and other materials, protecting the measurement from electrical interference on both sides of the plain insole (3). The plain insole consists of layers 1 and 2 shown in figure 5. The protective coating, which is applied when constructing the coated insole is explained in the next subchapter.

FIGURE 5 Smart insole structure

2.4 Coated insole

The coated insoles are the penultimate version of the insole before it is assembled into the final product. The coated insole is coated with a protective sole material which is glued to the top and bottom of the plain insole. The protective coating is applied to the smart insoles to protect the plain insole and to help the smart insole function better in normal use cases. The structure of a coated insole is shown in figure 5 with all three layers, and it is the final structure of the insole component of the smart insole.

3 TEST HARNESS REQUIREMENTS

The primary purpose for this thesis was to clarify what the requirements are for the test harness. Each separate part in the test harness will have limitations and ranges of units they are capable of functioning within. Therefore, the requirements set by the tested devices and the use of the test harness need to be defined before any decisions can be made on any use of technology in the harness. The requirements set by varied factors in the testing and calibration process are discussed in this chapter. Each subchapter has a table of requirements at the end including each requirement that was mentioned in the subchapter to increase readability. The requirements conclusion subchapter merges the requirements of each previous subchapter together into one concise table. Figure 2 explains the main components of the test harness.

3.1 Generic test harness requirements

This subchapter describes the requirements that are set for the test harness regardless of what DUT is being tested. Most of the requirements covered in this subchapter are related to the test system control device and the interfaces between it and the reference force test equipment. The requirements set in this chapter can be found in table 2.

3.1.1 Test head

The test head should also be interchangeable between test heads with different sizes because the test head used for the plain sensor and insoles is different. Two examples of different test head structures are portrayed in figure 6. A spindle with ISO standardized M6 or M8 threads should be used on the test head as a method of attaching it to the reference force test equipment. (4.)

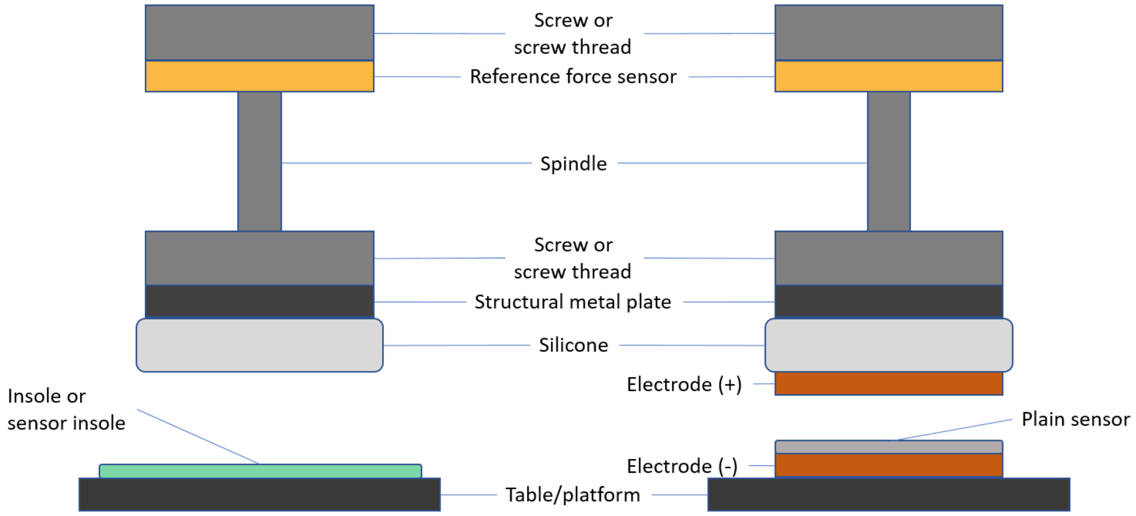

FIGURE 6. Test head structures. Test head for insole or smart insole as DUT is shown on the left and test head for plain sensor as DUT is shown on the right. Component proportions do not represent the real-life proportions.

The test head should have elastic rubber material, e.g. silicone, on its tip to press the DUT effectively and safely. The rubber material needs to be able to withstand at least the same amount of force, when it is pressed, as the DUT without losing its elastic properties. The horizontal expansion of the rubber material during compressions needs to be considered when figuring out the test head pressing area where the force is applied, because when it is pressed vertically, it will spread out to the sides and thus affect a larger area of the DUT. The silicone tip helps the actuator to press the DUT over a longer duration by giving it the possibility of movement. The test head also needs to be able to move approximately 50 mm from the table to allow to move the DUTs and change the test head or its components, such as the rubber material on the tip.

3.1.2 Test table

The table on which the DUT will be placed during the test will be either static or dynamically moving. This will determine whether the test harness is semi-automatic or completely automated. When using a static table, the operator needs to move the insole or smart insole between presses before the test or calibration sequence can continue. With an XY positioning table moved by stepper motors, the test system control device would be responsible for moving the table underneath the DUT to press different sections on it when testing or calibrating insoles or sensor insoles. The table also needs to be able to withstand the maximum amount of force applied by the reference force test equipment without bending or otherwise affecting the measurements.

When using a positioning table, the test system control device needs a way to know where the insole is on the table so that it can control the movements of the table accurately. There are a few methods that the test system control device can use to track the location of the sensor, e.g. a jig for each DUT size with preprogrammed positions, an infrared distance sensor, or a light dependent resistor or a camera that tracks markings on the DUT. The three DUTs, i.e. plain sensors, plain insoles and coated insoles are all of different colors and allow different types of markings thus the origin point locator might become complex to implement. Choosing the technology to use for this is outside of the scope of this thesis because the initial requirements only demanded a static table.

3.1.3 Test environment

The use environments of the test harness will most likely be a dedicated test area in production, and a laboratory room in an office building with tens of people working in multiple rooms during office hours. It would be beneficial for the test harness if the reference force test equipment could operate silently, and without excessive vibration to avoid generating noise through other objects. Achieving a completely silent test harness of this type will most likely be nearly impossible and it should not be a high priority. Unnecessary noise generated by the test harness should still be avoided so that the office floor would not be polluted with noise when the test harness is operated. The test harness will be operated in a production setting, thus the hazardous environment of an industrial production area must be taken into consideration. This means that the test harness must be capable of operating in an area where particles from other production machinery contaminate the air, the electrical properties of the environment are different from regular indoor environments and where several people operate on a daily basis.

The test harness needs to be safe for the operator to use. The reference force test equipment should not be able to e.g. crush the finger of the operator during a compression. The safety of the operator needs to be upheld by using some form of safety controls so that the reference force test equipment will not be able to operate when unsuitable objects are in the test area where hazardous incidents might happen. One method of eliminating possible hazards is using light curtains to make sure that the test harness does not function when the operator interferes with the test area.

To avoid test harness malfunction due to, e.g. overdriving the actuator used by the reference force test equipment, the reference force test equipment should have a modular automatic kill switch in the hardware of the harness to cut off the current from the actuator driver or motor. The kill switch should not close the entire test harness, but only the driver or motor used to actuate so that the reference force test equipment can notify the test system control device of a failed compression. The component that triggers the kill switch needs to be modular and completely separate from the reference force sensor in case of a malfunction or a mismeasurement in the sensor. With a modular kill switch trigger component, higher or lower thresholds are allowed for tests with different force ranges.

The maintenance of the test harness should be made possible by a person with sufficient knowledge about it, e.g. repairs to the force test equipment should be possible without having to remanufacture the whole device and software re-implementations or bug fixes should be possible to introduce to the test system control device.

3.1.4 Software and user interface

When smart insoles are assembled and tested in production, product identification data needs to be stored into a database for traceability reasons. Each produced StepLab smart insole needs to be documented with, e.g. an identification number, a date of assembly and calibration values so that they can be traced and identified after production for warranty and support cases. Some of the data will be automatically recorded by the test harness and some of the data must be inserted by the operator. Thus, the user interface should allow for entering and editing numbers and letters. The data that is stored needs to be saved reliably into a database or a text file at least in two separate locations, e.g. a cloud service, a flash drive or an internal storage. An internet connection on the test system control device is not necessary but it would make off-site data acquisition more efficient. Having an internet connection could also allow connecting to the test system control device, allowing off-site support if the test harness malfunctions during the use.

The test harness needs a user interface to inform the operator of the ongoing test phase status. It needs to be able to show whether the executed test task was successful or not and whether the tested insole can be taken to the next step on the production line. The operator should also be able to operate the tool and get visual feedback on the task at hand. A touch screen is not a necessity, but it would be highly preferable for simple visual feedback, instructions in written form and operator inputs through the same interface thus creating an efficient and streamlined user experience. A suitable alternative would be a keyboard, a mouse, and a monitor interface.

The pre-existing automation scripts and calibration software tools, which will be used with the test harness, are written in C and Python programming languages and they are compiled and executed on a 64-bit Linux system. Some of these will be used with the test harness to ease and automate the DUT testing and calibration. To reduce the amount of changes to be made on the pre-existing systems, the test control system should be able to run this software. A Linux system would be preferable for the versatility of BLE tools and control interfaces, for the ease of use, and because the pre-existing software has only been confirmed to function as expected on a 64-bit Linux system.

The test system control device needs to be able to give commands to the reference force test equipment. Using a USB interface to handle this communication would be the easiest and simplest to implement while using a PC as the test system control device. Other methods of communication, e.g. a wireless protocol or a serial port, are acceptable, but not preferable. The software, which is used to control the reference force test equipment, should also be capable of being integrated into the system so that the functionality of the software in the test system control device would work as seamlessly as possible. The software used on the test system control device should not be too difficult to operate for someone who has limited experience with computers.

Reference force data should be readable from the test head of the reference force test equipment to ensure that the calibration is accurate. The test head should have a reference sensor on it to measure the generated force during compression. Without the sensor, the system control device would have to rely on the accuracy of the reference force test equipment linearity over time instead of having correctly measured force each time the test head is used to press the DUT. This sensor could be either integrated into the reference force test equipment or a separate module that is connected to the system control device for data acquisition. The preferred interface between the reference force sensor and the system control device is via a USB interface. A controller device may need to be used to read out the sensor values and the controller is the device that relays the sensor signal to the system control device. The accuracy of the reference force sensor must be certified by a certification body and it must be calibrated accordingly to ensure that the sensor is accurate. The accuracy, sensitivity and precision of the sensor measurements should be better than the DUT to properly catch the deviation between the applied force and what is measured on the DUT. The reference force sensor should also be modular so that the reference force sensor could be changed for different testing purposes. Having a modular reference force sensor would mean that different types of force tests could be done for R&D purposes.

The test harness and its operator should be ESD protected by having the same electric potential. This is required to avoid electrical interference during use and to avoid causing malfunctions in the DUTs and the hardware used during calibration and testing.

TABLE 2. Generic requirements

Requirement	**Value**
Low noise generation when the test harness is used.	
User interface indicating the operator of the test phase status.	
The test system control device should run a Linux system.	

USB communication interface between the test system control device and reference force test equipment.	
Reference force test equipment control software integrability with system control device software.	
User interface and software used by the test harness operator should be easy to use.	
Data storage should be possible either locally on the test harness or online.	
The test head needs an accurate reference force sensor that communicates with the system control device.	
The reference force sensor must be certified by a certification body and calibratable.	
Changeable reference force sensor.	
The reference force sensor must be more accurate than the DUTs.	
A kill switch for the actuation mechanism with a modular trigger component that is separate from the reference force sensor.	
Capability of adding a XY positioning table to the reference force test equipment.	
Safety of the test operator must be upheld by a safety system in the test harness.	
The industrial production environment must be considered when developing the test harness.	
Maintenance and repairs on the test harness should be possible.	
The test harness should have the same electric potential as the operator to be ESD protected.	
Test head minimum vertical upwards movement from the table surface.	50 mm

3.2 Requirements set by plain sensors

The plain sensor tests are the first tests executed with the test harness. Each plain sensor needs to be tested at three different placements on the plain sensor before they can be placed in a plain insole. The requirements listed in this subchapter can be found in table 3.

3.2.1 Size and dimensions

To test the entire area of the plain sensor at different sections, the test head in the reference force test equipment needs to be relatively small. An ideal default test head for plain sensor tests would be approximately 10 mm in diameter and circular in shape.

The dimensions of the largest plain sensor that will be tested are 70 mm x 70 mm. The test table must be at least 100 mm x 100 mm to comfortably hold the largest plain sensor to be tested.

The initial plan is to use a static table, but the test harness should be modifiable to have a positioning table capable of moving in two dimensions. If a positioning table is used, it needs to be able to move accurately so that the reference force test equipment can press different sections of a plain sensor precisely. The area of the smallest plain sensor is approximately 550 mm^2 and each plain sensor needs to be tested at three different sections. The positioning table should be able to move accurately to the test areas of the sensors that could be close to each other or even overlapping with the 10 mm diameter test head. The positioning table should be able to move the plain sensor long enough distances so that the reference force test equipment can compress each plain sensor on the sheet. This means that the minimum moving dimensions of the positioning table are the distances required to move from one end of a plain sensor to the other end. The approximate minimum dimensions for the positioning table movement when testing plain sensors are 50 mm x 50 mm. The test table should also not cause electrical interference in the measurements or otherwise affect the measurements.

3.2.2 Mechanical measurement requirements

The force change data gathered from the sensor is linear. The linearity of the sensors means that the sensor signal reading is directly proportional to the acting dynamic force and the press speed. To achieve a completely linear test system, it is necessary that the force and speed of the reference force test equipment would be linear as well. (4.)

When the DUT is a plain sensor, electrodes need to be in contact with it so that the charge of the electrodes can be measured. The electrodes should be approximately 5mm thick and they should have connectors so that the charge can be read on a device. The electrodes should be made of conductive copper material.

The sensitivity of a plain sensor measurement is different compared to a plain or coated insole measurement. The electrode area in a plain sensor measurement is different from the electrode area inside an insole. The distance between the positive and negative electrodes are also not the same for plain sensors and sensors in an insole. The sensors that reside inside an insole have supporting material around them, thus the electrodes are not as close in contact with the plain sensor as they are in a plain sensor test where the plain sensor is placed on a negative electrode and pressed with a positive electrode.

The difference between the voltage measured from the electrodes can be explained with the capacitance of the sensors in each measurement. The equation in formula 1 is used to calculate the capacitance of an assembly where two equal area parallel plates are separated (5).

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$ *FORMULA 1*

C = capacitance (F)

ε_r = relative dielectric constant of the material (F/m)

ε_0 = dielectric constant of free space (F/m)

A = area of the electrodes (m^2)

d = separation between the electrodes (m)

As seen in formula 1, a larger electrode area means a higher capacitance and a shorter distance also means a higher capacitance. In a plain sensor measurement the test head area, which determines the electrode area, is smaller than the area of the sensor, while the electrode area in an assembled insole is larger than the area of the sensor. Due to the structure of the plain insole, the electrodes are slightly further apart than they are in a plain sensor test. In previous tests, it has been noticed that depending on the electrode area, these differences cause the plain sensor measurements to be approximately 2-4 times as sensitive as plain or coated insole tests with the same forces. This is caused by the capacitance of the plain sensor measurement assembly being lower than the plain or coated insole capacitance. As seen in formula 2, with a lower capacitance, the measurement voltage is higher if the charge remains the same, i.e. the force applied on the sensor is the same (5).

$$V = \frac{Q}{C}$$ *FORMULA 2*

V = voltage (V)

Q = charge (C)

In terms of requirements, the plain sensor sensitivity means that the force applied in the plain sensor tests should be smaller than the force applied in the plain insole and coated insole tests. The force should be applied over the same amount of time in both tests though. With good planning and design of the test head, a force that is half as strong as the one used for the insole tests should be adequate. The nominal force applied in the plain insole and coated insole tests, discussed later in this thesis, will be used to determine the numerical values for the plain sensor test requirements.

When plain insoles are tested, a 50 – 100 N pre-compression needs to be applied by the reference force test equipment to get a full contact with the plain sensor and electrodes. It was noticed in manual compression tests that if there is no pre-compression applied to the sensor before applying the force, the measurements would not be precise. This issue was resolved by adding a small extra weight on the pressing tool that compresses the sensor down without applying manual force. The total force applied with the pre-compression and the measured force summed up should be equal to the nominal force required for the plain sensor tests. The pre-compression must be compensated for with a constant variable in the software of the test system control device. With the preceding press, the pre-compression force would be read from the reference force sensor because the pressed plain sensor might not measure the force of the pre-compression correctly. The sensors within plain insoles do not have this problem as their electrodes are already in contact with the plain sensor.

The test head must be perpendicular to the DUT, meaning that it needs to press the DUT flat with a 90-degree angle. The perpendicularity of the test head to the DUT must be measurable and if any deviation to perpendicularity is discovered, e.g. after disassembling and reassembling the test harness or after use, the deviation needs to be either correctable or compensable, e.g. with a ball joint added to the test head structure, shown in figure 7.

FIGURE 7. Example picture of a ball joint. (6.)

TABLE 3. Requirements set by plain sensors

Requirement	**Value**
Force applying must be linear.	
Default test head size (circular diameter).	10 mm
Test head must be switchable to a smaller or larger size test head with a screw.	M6 or M8 screw thread
The test head should have elastic rubber material at its tip to allow for actuator movement in reliable time.	
Elastic rubber material needs to be able to withstand the maximum forces applied with the reference force test equipment.	
A pre-compression force must be applied to the plain sensor before the actual measurement.	50 – 100 N
The test head must be perpendicular to the DUT.	
Test head to DUT perpendicularity must be measurable and correctable if misalignment happens.	
The test table should not cause interference in the measurement or otherwise be detrimental to the measurements.	
Minimum dimensions of the test table (including possible non-rigid extension platform).	100 mm x 100 mm
Minimum movement capabilities from origin point of XY positioning table.	50 mm x 50 mm

3.3 Requirements set by plain insole and coated insole tests

Plain insoles and coated insoles are not the same DUTs, thus their requirements were considered separately. However, most of the requirements for their tests were the same, therefore they were grouped into one chapter. For example, the flat dimensions of both types of insoles are the same, even though their thicknesses are not. The plain insole and coated insole tests also require applying linear force applying from the test harness, a default circular test head with an approximate diameter of 10 mm and the test head should be switchable to smaller or larger test heads with a screw similar to the plain sensor tests. The requirements listed in this subchapter are found in table 4.

3.3.1 Smart insole normal use forces

To figure out the ranges of forces that the smart insole will be used in, measurements must be taken to find the maximum vertical forces at the minimum and maximum press times. These measurements were not used as absolute requirements for the test harness because they are the absolute minimum and maximum values where the smart insoles will be used, but not necessarily the required values that need to be tested with the test harness. To keep the test harness development costs relatively low, the requirements should not be too excessive. The main functionality of the test harness is to test and calibrate the sensors at sensible force ranges, although any extra capabilities would be preferred for R&D purposes. To figure out the limitations for the test harness that are still useful, previously executed tests were referenced. The tests conducted were done using an AMTI BP600900 force plate as a reference force plate.

A worst-case scenario step with a smart insole is shown in figure 8. The graph represents force measured with the AMTI force plate. The depicted data was found to be the highest force inducing measurement from a single step which was singled out from a large collection of previously recorded steps. These steps were measured during a test conducted prior to working on this thesis on 25 test subjects walking at different speeds and the selected step data graph was chosen from the highest weighing individual walking with a fast pace. The individual weighed approximately 139 kilograms and put most of the force of their steps on the heel impact.

The maximum measured force during the force curve in figure 8 is 1,731 and it took 170 ms to reach the maximum force F_{max} from the start of the step F_0. There’s a slight dip on the rise from F_0 to F_{max}, which was seen in some of the data, but for the purposes of this thesis it can be disregarded. In reality, the force to the force plate rose consistently to the maximum value. To approximate the highest force that would be applied to one sensor on a heel step, such as this, the maximum force value needs to be divided by the number of sensors that receive the heel impact. The force impact on the heel area of the smart insole is distributed to three sensors. Rounding the maximum force up to 1,800 N and dividing it by three gives an approximation of 600 N as the maximum force per sensor in normal use. Thus, the absolute upper limit for the reference force test equipment is F_{max} = 600 N on a sensor over 170ms. This result gives an approximate speed of force of 3,500 N/s for the $F_0 \rightarrow F_{max}$ portion of the curve. A force of 600 N is unlikely to happen in a realistic use case of the device. However, it was still used as a reference point in this thesis to have a maximum force that is slightly above the necessary limit.

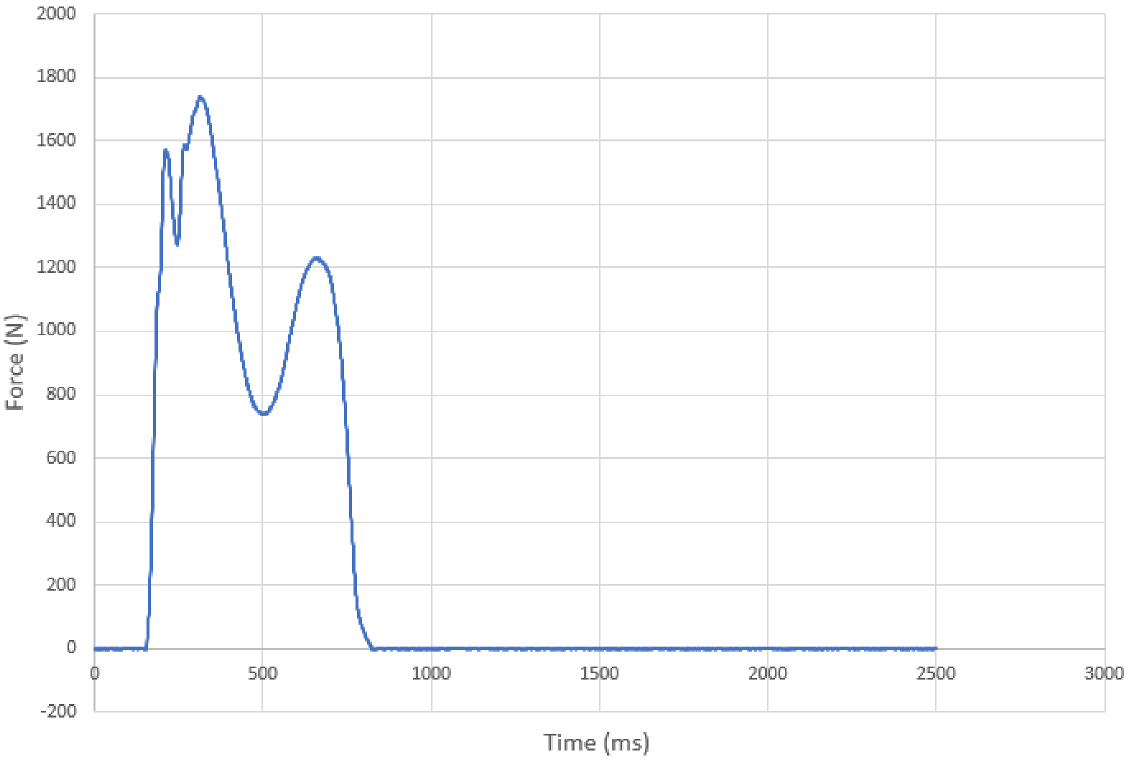

FIGURE 8. F/t data graph of a fast and high-force worst-case scenario step

The reference force test equipment should be capable of applying forces slow as well as fast. The maximum time to reach the maximum force was tested similarly with the same test subject walking at a slow walking pace. Measurement data of this step is pictured in figure 9, where the step duration is longer than in the fast step in figure 8.

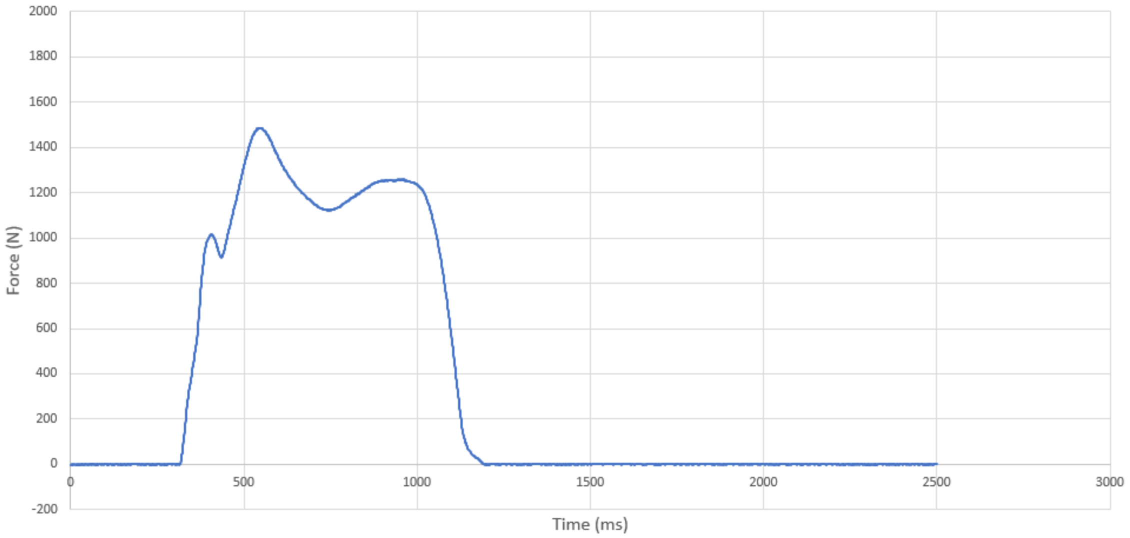

FIGURE 9 F/t data graph of a slow and high-force step

The reference force test equipment does not necessarily need to apply the maximum forces that the DUTs can measure. A nominal force of approximately 300 N should be enough for plain insoles and coated insoles based on tests conducted with varying levels of force. If the reference force test equipment is capable of forces over 300 N, those forces could be used in R&D use, while tests with 300 N or less could be used to test the functionality of the sensors in the insoles and for calibrating the sensors in the insoles. It has also been noticed that in tests, the time that the force is applied in is typically between 150-500 ms thus the nominal time to apply force should be 300 ms (4).

3.3.2 Other requirements

The test head requirements for the plain insoles and coated insoles are the same as for the plain sensors, except that there is no need for a pre-compression or electrodes. The electrodes should be removable from the test head and the test table so that they do not interfere with the tests done on plain insoles and coated insoles. Even though no pre-compression is required for the insole tests, the ideal case is where the test head is lightly pressed against the DUT before actuating.

The test system control device must be able to communicate with the smart insoles during the calibration or testing performed by the test harness as shown in figure 2. The BLE interface, which is implemented in the smart insoles, can be used for communication between the DUT and the test system control device. Most of the necessary calibration and testing software is already implemented in the embedded software of the smart insoles and could therefore be easily used if the test system control device is a central BLE device.

The table platform should be large enough to hold the insole. The smart insole cable and electronics casing can be placed on a non-rigid platform which can move with the table if a positioning table is used. The maximum area dimensions of a complete smart insole system with a European shoe size 46 are 278mm x 293 mm as seen in figure 3. Thus, the dimensions of the table platform including the extension platform for the cable and electronics casing should be at least 400 x 400 mm. If a positioning table is used, it needs to be able to move the actuation point from one sensor on the insole to another so that the reference force test equipment can press different sensors without requiring the test harness operator to move the insole. It should be able to move a long enough distance to reach from the lowest heel sensor to the upmost big toe sensor in the smart insole in one direction and from the left-side corner of the leftmost sensor to the right-side corner rightmost sensor at the ball of foot section of the smart insole. The largest smart insole (shown in figure 10) was measured to have approximate dimensions of 293 mm x 93 mm excluding the cable and electronics casing which can be placed on a non-rigid extension platform. The table should be capable of some extra movement to allow for further sizing up the smart insoles and for diversity of use. The minimum movement requirements for the table are 170 mm from the origin point along the X axis in both directions and 80 mm from the origin point along the Y axis in both directions, which should be enough for the intended purposes.

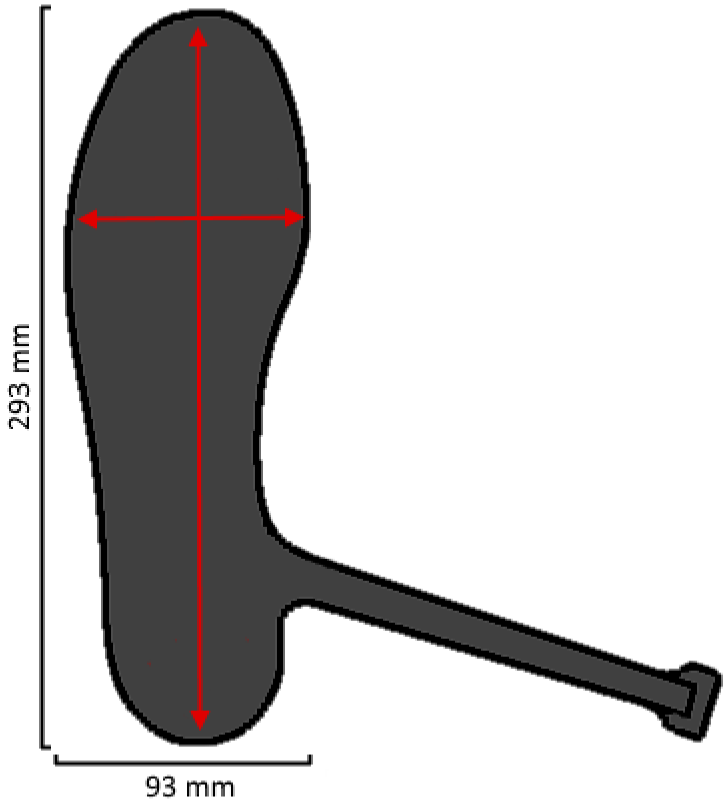

FIGURE 10. Absolute minimum positioning table movement dimension measurements for insoles

Because the test harness will be used for R&D purposes in addition to being used as a production tester, the reference force and speed of the press test head need to be modifiable. By allowing an easy and accurate modification of these parameters, the test harness could be used for multiple different purposes in R&D testing and it could possibly even be used for simulation purposes.

TABLE 4. Requirements set by plain insoles and coated insole tests.

Requirement	**Value**
Force applying must be linear.	
Default test head size (circular diameter).	10 mm
Test head must be switchable to a smaller or larger size test head with a screw.	M6 or M8 screw thread
The test head should have elastic rubber material at its tip to allow for actuator movement.	

Elastic rubber material needs to be able to withstand the maximum forces applied with the reference force test equipment.	
Nominal applied force.	
Nominal time to apply force.	300 ms
The test table should not cause interference in the measurement or otherwise be detrimental to the measurements.	
Minimum dimensions of the test table (including possible non-rigid extension platform).	400 mm x 400 mm
Minimum movement capabilities from origin point of XY positioning table.	170 mm x 80 mm
Modifiable reference force and speed values for the reference force test equipment.	
Wireless BLE communication as a BLE central device.	

3.4 Requirements conclusion

This subchapter contains the generic requirements and the requirements set by plain sensor, plain insole, and coated insole tests. The requirements that were listed in the previous chapters were merged together in table 5, which is one concise table where the requirements are listed by each test case, split into requirements for different portions of the test harness. The general test harness requirements must be considered when choosing each component of the test harness.

TABLE 5. Merged requirements from tables 2-4

Requirement	**Plain sensor**	**Plain insole**	**Coated insole**
General test harness requirements			
Low noise generation when the test harness is used.	x	x	x
User interface and software used by the test harness operator should be easy to use.	X	x	x
User interface indicating the operator of the test phase status.	X	x	x
Safety of the test operator must be upheld by a safety system in the test harness.	X	x	x
The harsh industrial production environment must be considered when developing the test harness.	X	x	x
Maintenance and repairs on the test harness should be possible.	X	x	x
Communication & software requirements			
USB communication interface between the test system control	X	x	x

device and reference force test equipment.			
The test system control device should run a Linux system.	X	x	x
Reference force test equipment control software integrability with system control device software.	X	x	x
Data storage should be possible either locally on the test harness or online.	X	x	x
Wireless BLE communication as a BLE central device.		x	x
Actuator & test head requirements			
Force applying must be linear.	X	x	x
A kill switch for the actuation mechanism with a modular trigger component that is separate from the reference force sensor.	X	x	x
Default test head size (circular diameter).	10 mm	10 mm	10 mm
Test head must be switchable to a smaller or larger size test head with a screw.	M6 or M8 screw thread	M6 or M8 screw thread	M6 or M8 screw thread
Test head minimum vertical upwards movement from the table surface.	50 mm	50 mm	50 mm
The test head must be perpendicular to the DUT.	X	x	x
Test head to DUT perpendicularity must be measurable and correctable if misalignment happens.	X	x	x
The test head should have elastic rubber material at its tip to allow for actuator movement in reliable time.	X	x	x
Elastic rubber material needs to be able to withstand the maximum forces applied with the reference force test equipment.	X	x	x
Modifiable reference force and speed values for the actuator.	x	x	x
A pre-compression force must be applied to the plain sensor before the actual measurement.	50 – 100 N	Light press	Light press
Nominal applied force.	150 N	300 N	300 N
Nominal time to apply force.	300 ms	300 ms	300 ms
Reference force sensor requirements			
The reference force sensor must be certified by a certification body and calibratable.	x	x	x
The reference force sensor must be changeable.	x	x	x

Communication interface with the test system control device.	x	x	x
The reference force sensor must be more accurate than the DUTs.	x	x	x
Test table requirements			
Capability of adding a XY positioning table to the reference force test equipment.	x	x	x
The test table should not cause interference in the measurement or otherwise be detrimental to the measurements.	x	x	x
Minimum dimensions of the test table (including possible non-rigid extension platform).	100 mm x 100 mm	400 mm x 400 mm	400 mm x 400 mm
Positioning table: Minimum movement capabilities from origin point.	50 mm x 50 mm	170 mm x 80 mm	170 mm x 80 mm

4 REFERENCE FORCE TEST EQUIPMENT TECHNOLOGY STUDY

The reference force test equipment will consist of five or more components depending on which technologies are chosen, as shown in figure 11. Each component needs to be compatible with the others and the choice of one component affects the choice made on every other component. The most preferable choices are examined in this chapter. Only the components whose characteristics and capabilities are necessary to know before ordering the reference force test equipment system from a manufacturer are studied in this thesis.

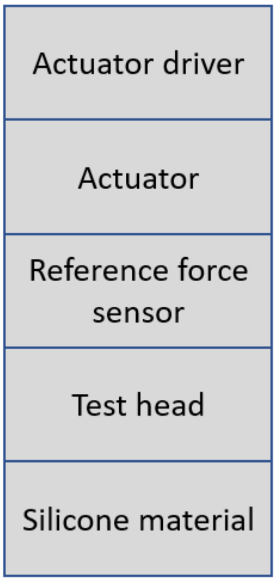

FIGURE 11. Reference force test equipment component stack

4.1 Vertical power transmission with actuators

The main functionality of the force test equipment is its capability to apply vertical force directly on a sensor. To do this, it needs to be capable of some form of power transmission to convert power to vertical force. The most common methods to achieve this are electrical and fluid power transmission methods. The methods will not be thoroughly examined in this thesis but the essentials that are required to make a choice between the technologies will be researched, because the development of the actuator will be ordered from another company.

4.1.1 Electrical actuators

The preferred options for electrical power transmission methods were chosen to be linear solenoids, which use electrical energy to actuate a plunger and power transmission screws, which convert rotary motion into linear motion. The three most commonly used power transmission screws are lead screws, ball screws and roller screws.

Linear solenoids

Linear solenoids are electromagnetic devices that can be used to generate mechanical push or pull force with electrical energy. They consist of an electrical coil that is wound around a cylindrical tube with a ferro-magnetic plunger that can move or slide in or out of the body of the coil as seen in figure 12. (7.)

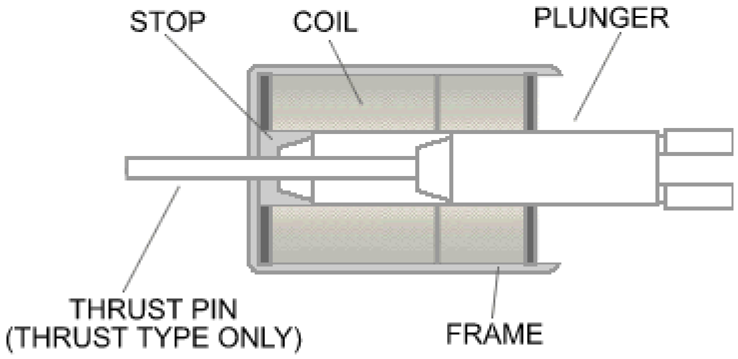

FIGURE 12. Cross section of a linear push solenoid (8.)

The force actuated by a solenoid is dependent on the stroke length of the actuator, the on-off duty cycle, and the current applied to the coil. By changing these three parameters, the force generated by the actuator can be changed. Figure 13 portrays the effects of duty cycle and stroke length in relation to actuated force. Linear solenoids usually have a small range of force at which it can operate. A reference force generating system with variable forces at varying speeds using solenoids would require several different solenoids to be changed between tests to achieve lower or higher forces. The input power required to use solenoids at force ranges that fit the requirements of the test harness are approximately 100 – 1000 Watts (9).

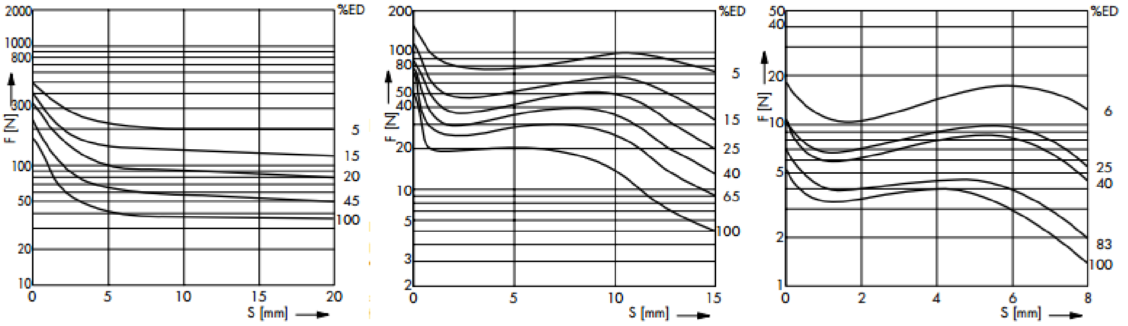

FIGURE 13. Force vs. stroke diagrams of some heavy duty linear solenoids by Kuhnke (10.)

The force generated by commercially sold linear solenoid actuators is not directly proportional to either the stroke length or duty cycle. Manufacturers often offer force vs. stroke diagrams such as the diagrams seen in figure 13, which can be used to estimate the actuated force if the duty cycle percentage is known. Linear solenoid force is, however, directly proportional to the speed of the actuator, which means that varying the speed by applying higher current or changing some other parameter also varies the force of the actuator.

Generating force slowly with linear solenoids would be problematic even with the use of extremely elastic test head rubber materials. A flexible spring would most likely have to be attached to the plunger to apply force slower. This, along with the range limitations make linear solenoids a challenging actuating mechanism to implement for the reference force test equipment. To use the reference force test equipment with solenoids, multiple changeable solenoids with different force ranges would have to be used, because the stroke length must be relatively short for this test harness. The automation speed of the test harness might also be hindered due to a linear solenoid duty cycle directly affecting the force actuated, meaning that the solenoid would need brief cooldown periods between actuations. This happens because the coil in the solenoid heats up over time when power is applied to it and its electrical resistance changes.

Lead screws

Lead screws consist of a lead screw and a lead nut with threads inside. They slide along the screw threads to convert rotary motion into linear motion. Lead screws have an efficiency of 20-80%, which is noticeably lower than the higher efficiencies of roller and ball screws. This is caused by the lead screws having much higher friction between the nut and screw, which also causes quicker wear, leading to a shorter life span of the screw (11). The higher friction also means that the power of the motor that is driving the lead screw must be high. Due to lack of efficiency of lead screws, they do not qualify as a probable option for the reference force test equipment.

Ball screws

Ball screws are mechanical assemblies consisting of a ball screw and a ball nut which are packaged as an assembly with recirculating ball bearings (see figure 14). The balls in the nut of the ball screw roll along the screw axis, converting rotary motion into linear motion along the screw. With this structure, the ball screw drive has a minimal friction coefficient and a high efficiency of over 90% in almost all applications, but it produces a significant amount of noise (12). For vertical applications, ball screws require a braking system to lock them in place to eliminate back driving and to ensure safe operation (13), which makes it more difficult to implement vertical motion using ball screws. Lubrication with oil or grease, depending on the application is required to keep the friction coefficient low and to avoid mechanical wear in the ball recirculation system. Ball screws are the most economical option when converting rotary motion into linear motion.

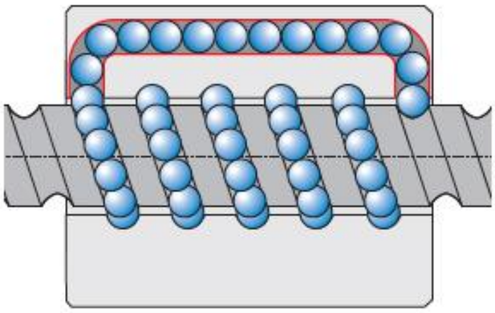

FIGURE 14. Cross section of an end cap recirculating ball screw (14.)

A method of generating rotary power needs to be applied to the screw to drive it. The most usual choices are DC motors, servo motors or stepper motors. For the reference force test equipment actuator, the chosen method of motor is either a servo motor or a stepper motor. They both require a control circuit, but servo motors have a more complicated setup and cost more, although in return they have more flexibility with torque. The motor must have a high enough torque to apply the maximum required force at the lowest required speed.

Ball screw force can be changed by altering the speed of the screw or by pressing the silicone material down further. Altering the speed can be done by controlling the motor that is driving the screw or by using a screw and nut combination with different threading angles and sizes. The ideal case would be one where neither the ball screw and nut nor the motor need to be changed between low and high force presses, but due to limitations with the motor running speeds it might become complex.

Ball screws have some issues to take into consideration when using them as actuators. The environment where the ball screw is used matters. If contaminants such as dust or larger particles get in the ball recirculatory system, the screw might suffer from wear when the balls grind the contaminant against the screw threads. The critical speed of a ball screw must be considered when choosing the ball screw to be used. The critical speed is the speed where the screw starts to resonate regardless of screw orientation, therefore it determines how fast the movement of the nut can be before the screw becomes unstable.

Manufacturers suggest that the ball screw should only be used at 80% of its critical speed to avoid failure or damage to the screw. Ball screws can also be worn out over time and they need to be replaced after a certain amount of use. The approximate life expectancy for a ball screw in revolutions can be calculated if the dynamic load, axial load and fatigue factor are known. Since the actuator in this test harness will be used for short distances, the life expectancy of a ball screw should be quite long. (15.)

Roller screws

Roller screws are comparable to ball screws in that they provide linear motion along the screw with low friction by using load transfer elements between the nut and the screw shaft. The difference is that roller screws use threaded rollers in the nut instead of ball bearings to transmit force. Roller screws have a larger load carrying capacity and increased service life compared to ball screws, but they are also more expensive. The benefits of roller screws over ball screws are not worth the higher investment for the test harness application because the load capacity of ball screws is adequate for the test presses and the actuator will not be running regularly for longer periods of time. (16.)

4.1.2 Fluid power actuators

Hydraulic pressure

In the context of this test harness, a hydraulic pressure system is a system where a liquid, most commonly oil, is used to transmit power from one location to another. Linear force is generated by applying pressure to one end of the system to move an actuator, i.e. a cylinder to the other end of it. In actual hydraulic pressure systems, the pumps contain pistons or other types of pumping chambers, driven by high speed motors or engines. These chambers draw fluid in and push it out to the hydraulic circuit in the process, generating pressure and pushing the actuator. (17.)

Hydraulic actuators are often aimed at high-force applications because of their ability to generate extreme force with a small size. Hydraulics will leak fluid, which will create issues with cleanliness and they require several different parts to work properly, ending up in a large system. The use of hydraulic actuators was considered unfit for the test harness because hydraulic actuators are usually used for high-force applications and most of them provide too high forces for the test harness. The fluid leakage would also create unwanted problems and environmental hazards in the use environment of the test harness.

Pneumatics

Pneumatics is a fluid power technology which works similarly to hydraulic pressure, but instead of using a liquid to transmit power, a gas such as air is used. Similarly to hydraulic linear actuators, pneumatic linear actuators consist of a piston and a rod moving inside a closed cylinder. When using air, it is usually applied to the system by pumping compressed air into a receiver. Other gases such as nitrogen can also be used with a pneumatic system, but regular air is most commonly used. Pneumatic systems are usually operated at much lower pressures than hydraulic systems, which means that the components can generally be made of much lighter and thinner materials than hydraulic pressure systems. The lower pressure also means that the actuators of a pneumatic system must be sized larger than their hydraulic counterparts to apply an equivalent force. If air is used as the gas to operate the system with, the system can be much simpler than a hydraulic system because the air can be exhausted to the atmosphere, instead of having to route the fluid back to a container, which also removes the hazard of fluid leaks. (18.)

Pneumatic linear actuators come in two different cylinder types: single acting and double acting. An actuator with a single-acting cylinder has a single port that allows the compressed air to enter the cylinder to move the piston. The piston is returned to the original position by either an internal spring or in some cases with gravity when the compressed air is released out of the cylinder. In the case of this test harness, a spring would have to be used to move the piston to its original position because the return movement is against gravity. Double-acting cylinders have two ports, one at each end to move the piston forward or back by alternating the port that receives the compressed air. A double-acting cylinder is unnecessary for the reference force test equipment because a spring inside the cylinder should be enough to return the piston to its original position. (19.)

Pneumatic linear actuators require a compressor to provide compressed air to a filtering and regulating system that is distributed to the actuator as needed by a control valve. A picture of the components in a basic pneumatic linear actuator system can be seen in figure 15. More components, e.g. a tank for the compressed air, pressure gauges, automatic water condension drains, safety valves, line filters, and speed controllers may be required in the system depending on the application. A network of tubes or pipes capable of having compressed air move through them are used to connect all these components together.

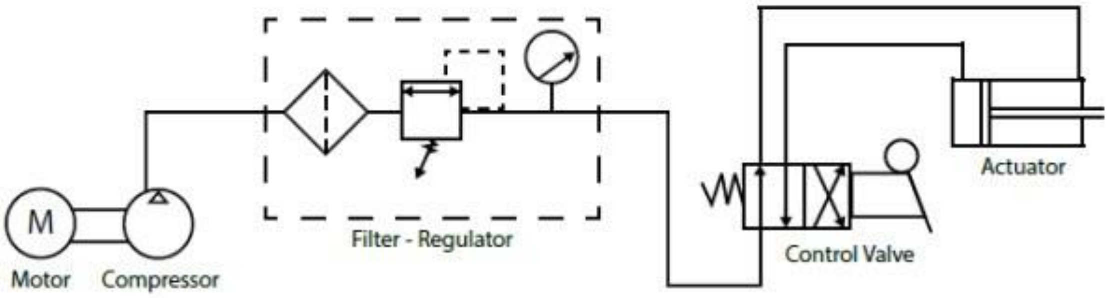

FIGURE 15. A typical pneumatic linear actuator system with a double-acting cylinder. The regulator determines the speed of the actuation and the control valve determines the force of the actuation. (18.)

Pneumatic linear actuators are often simple compared to other actuators because they have few limiting matters when it comes to use environment and mechanical wear. They also provide precise linear actuation accurately with a great repeatability, but they are often loud, not only because of the pressurization and depressurization of the piston, but the air compressor also generates a lot of noise. Pneumatic actuators are often low-cost without accurate control, lightweight and require less maintenance than other actuators due to durable components. However, by increasing accuracy and range, the efficiency drops and the costs and complexity increase to levels where the system might not be easier to implement than other linear actuation systems. Calculating the actuation speed is a complex task when developing the system with a pneumatic system because the friction of the air moving in the pipes and components increases in a non-linear fashion. Friction losses could be reduced by changing some of the system components, which means that in the case of the test harness and its relatively wide range of actuating forces and speeds, a pneumatic actuation system might be required to either have a modular cylinder, larger and shorter tubing, or other changeable components. (18; 19.)

4.2 Test head sensor

Many kinds of commercially sold sensors to measure force exist, such as capacitive force sensors, strain gauges, piezoelectrical force sensors and conductive polymer sensors. Strain gauges and piezoelectrical force sensors were most commonly used for similar purposes, thus they were further researched to see which would be the best fit for the reference force sensor.

4.2.1 Piezoelectric force sensors

Piezoelectric force sensors are sensors that are created from a quartz crystal element and other components which generate a high-impedance electric charge proportional to the input force applied to it. The force applied to the piezoelectric sensing element produces a separation of charges within the atomic structure of the material which generates the output voltage. ICP (Integrated Circuit Piezoelectric) sensors or variations of them are commonly used to simplify the sensor system. In ICP sensors, the output voltage is either amplified or converted into a low-impedance signal within the sensor and the signal can then be used as an input data source for force measurement, e.g. on a microcontroller or SoC. The cross section of an ICP sensor by PCB Piezotronics is shown in figure 16. (20; 21.)

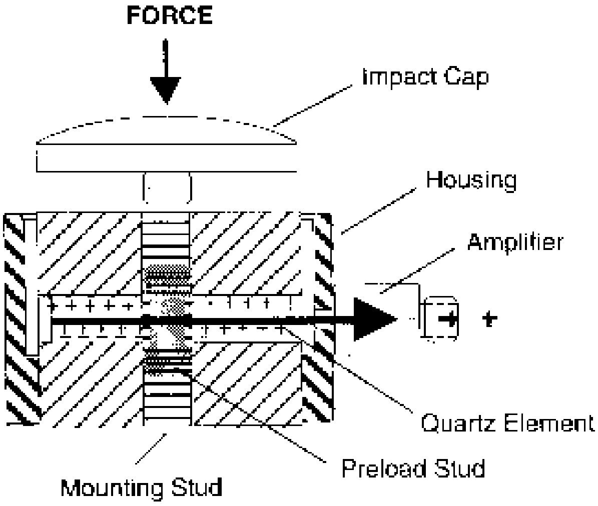

FIGURE 16. Example of an ICP sensor. (21.)

Piezoelectric force sensors measure dynamic force, which might make the use of them unnecessarily complex for the test harness application. They also have the issue of not being able to measure dynamic force when it is applied slowly.

4.2.2 Strain gauge based force transducers

A strain gauge is a sensor that has a resistance that changes when it gets thinner and longer as it is stretched. Strain gauges usually consist of a fine metal wire or foil arranged in a grid pattern covered with some carrier material to protect the metal grid. They are usually used to measure mechanical quantities of items that need to be tested, but they can be used as a force measurement sensor as well. Strain gauges measure strain, thus in addition to force, pressures, tension, weight and other properties can affect its resistance which is measured from the sensor and used as data to read the force applied to the sensor. Strain gauge sensors are used to measure static force, therefore even extremely slow applying of force can be measured. (22; 23.)

Most force transducers use strain gauges to function, with one, two or four strain gauges connected in a Wheatstone bridge circuit, making a quarter-, half- or full-bridge configuration (shown in figure 17). A full-bridge circuit force transducer should be used for the highest sensitivity, lowest noise and least amount of measurement error. The strain gauges are attached to the body of the transducer so that they would undergo the same deformation that the transducer body does, e.g. stretching and contracting. The output signal from the Wheatstone bridge circuit portrays the deformation of the strain gauges. This signal is linearly proportional to the change of resistance and thus also linearly proportional to the strain. Using a force transducer based on strain gauges is often a better choice than a plain strain gauge due to ease of installation and more reliable alignment of force. Force transducers usually have a spring element to allow repeatability and to remove the effects of lateral force. The properties of the transducer can be changed by using a different kind of spring or modifying the Wheatstone bridge circuit to compensate for the effects of temperature, lateral force and bending torque. (23.)

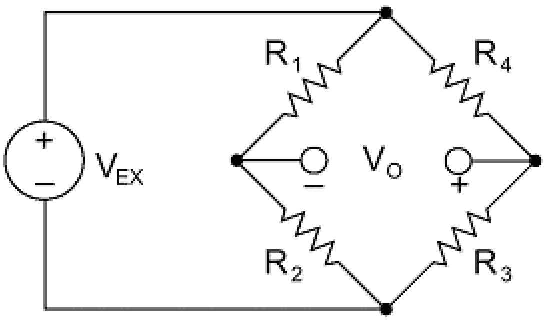

FIGURE 17. Wheatstone bridge circuit. The resistors can be changed with strain gauges. (23.)

5 REFERENCE FORCE SENSOR STUDY

Due to the calibrations that need to be done to the reference force sensor, it was noticed that it would be beneficial for the test harness to handle it as a separate component from the reference force test equipment. The reference force test equipment should have a M6 or M8 screw in place in the test head to attach the reference force sensor as shown in figure 6.

Force transducers come in varying ranges of measurable force and one with an acceptable range needs to be found to be used in the test harness. After some research had been done, it was found that the best readily available force transducer on the market would be an s-shaped load cell manufactured by HBM with the product identifier S2M, shown in figure 18. The S2M has several different options for ranges with nominal rated forces ranging from 10 N to 1 kN, where the 1 kN maximum measurable force limit would be sufficient for the test harness uses. The accuracy of the force transducer is 0.02%, meaning that at the nominal rated force of 1 kN, the result is accurate to 0.2 N. (24.)

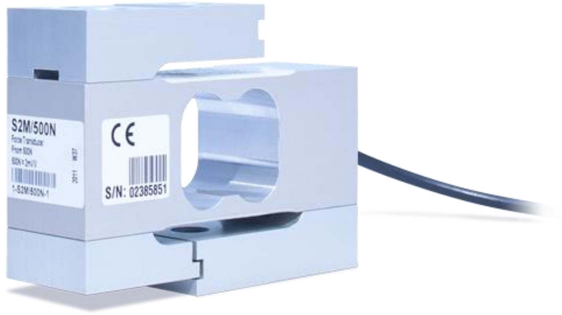

FIGURE 18. S-Shaped S2M force transducer by HBM (24.)

The six-wire connection in the S2M that is shown in figure 19 can be connected to an amplifier and ADC (analog-to-digital converter) setup to read the measurement signal. A four-wire connection can also be used by connecting the sense leads to their corresponding supply leads. In a four-wire connection, there will be a voltage loss on the supply leads because of the cable resistance that is compensated for in a six-wire circuit. The voltage loss can be compensated for with calibration and estimations, but it creates extra complexity to the sensor system. (25; 26.)

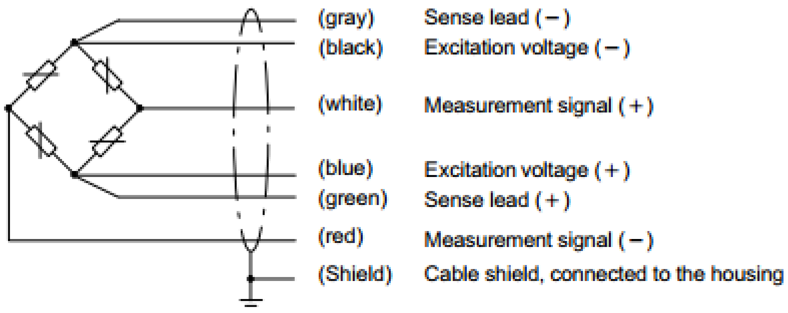

FIGURE 19. S2M pin assignment in a six-wire circuit (25.)

The operating range of the excitation voltage of the Wheatstone bridge in the S2M force transducer is 0.5 …12 V. The nominal rated sensitivity of the S2M is 2 mV/V, meaning that for example at 5 V excitation voltage, the measured signal is 10 mV when the force transducer is loaded with the nominal rated force of 1 kN. The resolution and sensitivity of the whole measurement depends on the electronics that are used with the force transducer, such as the amplifier used with it. The force transducer requires an amplifier and an ADC setup to read out the measurements for instance on a PC. The ADC should have a high enough resolution to reach sufficient sensor readings.

There are commercially sold amplifiers specifically designed for Wheatstone bridge components, such as strain gauges. The amplifiers are designed to amplify the signal from the sensor and to turn the analog signal into digital so that it can be read on a computer. Most of them use RS232, RS485 or USB interfaces as the output interface which is used to transfer the data onto a PC. Most of the amplifiers also have software used to read and log the data from the ADC that is sold together with the hardware. The amplifiers range from a 16-bit resolution to a 24-bit resolution. The voltage resolution range of these amplifiers can be calculated by dividing the voltage range by the maximum number of digital values that can be represented with the available bits. The formula for voltage resolution can be found in formula 4. The smallest detectable force change is something that is determined by the characteristics of the amplifier and by manually configuring the configurable parameters of the amplifier.

$$Voltage\ resolution = \frac{\Delta V}{2^b} \times 1000 \qquad \textit{FORMULA 4}$$

ΔV = voltage range

b = ADC bit count in the amplifier system

The force transducer and amplifier combination needs to be further researched, but it is outside of the scope of this thesis. The force transducer also needs to be calibrated to get a reliable measurement signal out of it. For the best results, the force transducer should be calibrated with the whole measuring chain i.e. the force transducer with the electronics used to read the signal from it (26).

6 CONCLUSION

The main objective of this thesis was to figure out the requirements for a calibration and test tool for the StepLab device production. Technology benchmarking and research were also requested after the requirements were found and provided. Some more detailed parts of the original scope of this thesis were cut out to be done later.

The requirements were relatively simple to figure out by discussing with other MoveSole employees, and by studying the technology behind the sensor used in StepLab products and testers used for similar purposes. My previous experience with the device and the software used with it helped with the learning process during this thesis. The technology research, however, was much more complex, as I had no previous knowledge about actuators or the mechanical characteristics of them. A significant amount of time was spent on studying how the different types of actuators function to get a grasp of the possibilities and limitations of the technologies.

Since the technologies to be used in the test harness were not chosen in this thesis, the technology related requirements for the actuators were not fully researched, even though some work on ball screw technology benchmarking and force transducer research were done. Ball screws, hydraulic actuator systems and force transducer systems will be researched further and benchmarked with the help of other MoveSole employees following the completion of this thesis.

Overall, I am satisfied with the results of the thesis, but the work on the subject has only begun and my new skills and knowledge will surely come to use when taking the project further.

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