© Strojniški vestnik 49(2003)2,76-89
ISSN 0039-2480
UDK 535.374:535.31
Izvirni znanstveni članek (1.01)

© Journal of Mechanical Engineering 49(2003)2,76-89
ISSN 0039-2480
UDC 535.374:535.31
Original scientific paper (1.01)

Laserski anamorfni profilomer

A Laser Anamorph Profilometer

Matija Jezeršek - Janez Možina

Prispevek opisuje načelo, razvoj, umeritev in testiranje laserskega anamorfnega profilomera. Profilomer deluje na podlagi laserske triangulacije z linijsko osvetlitvijo površine in digitalno obdelavo posnetih slik. Z vključitvijo anamorfne optike je dosežena prilagoditev merilnega območja v navpični smeri in posledično tudi večja ločljivost sistema vzdolž navpične smeri. Sistem se odlikuje s čvrsto in modularno konstrukcijo, natančnostjo ter z izvirno zasnovanim postopkom umeritve, ki omogoča hitro in zanesljivo merjenje.

(Ključne besede: profilometri laserski, optika anamorfna, razvoj, umerjanje, preskušanje)

This paper presents the principle, development, calibration and testing of a laser anamorph profilometer. A profilometer is based on the laser-triangulation principle with a laser plane projecting on the surface and digital processing of the acquired images. A lens with anamorph optics is used to fit the vertical measuring range and, consequently, to increase the vertical resolution. The system excels in terms of its robust and modular construction, its precision and uniquely designed calibration procedure, and its ability to make fast and reliable measurement.

(Keywords: laser profilometers, anamorphic optics, development, calibration, testing)

0 UVOD

Metode merjenja oblike teles na temelju laserske triangulacije se v svetu iz dneva v dan bolj uveljavljajo na številnih področjih. Med najzanimivejše primere uporabe teh metod spadajo dimenzijski nadzor izdelkov, robotska navigacija, diagnostika v medicini ter digitalizacija muzejskih predmetov [1]. V mnogih primerih pomeni uporaba brezdotične metode merjenja edino možnost. To so predvsem primeri, ko imamo opravka z gibajočim se merjencem, kadar je treba meriti obliko mehke površine in/ali v primeru težkih delovnih razmer na mestu merjenja. Kot skrajni primer naj omenimo geometrijski nadzor izvlečenega gumijastega traku takoj ob izstopu iz orodne glave [2]. Temperatura traku je tam še izredno visoka, guma je še v napol tekočem stanju in kar je najpomembnejše, nadzor je treba izvajati brez ustavljanja postopka izdelave.

Laserski anamorfni profilomeri (LAP), predstavljeni v tem prispevku, temeljijo na že omenjeni laserski triangulaciji. Laserski projektor ustvari svetlobno ravnino, katere presečišče z merjeno površino vidimo kot lasersko črto. Ta se skozi anamorfni objektiv preslika na zaznavni element kamere. Črta na sliki je zaradi razmaknjenosti projektorja in kamere ukrivljena skladno z merjenim profilom površine.

0 INTRUDUCTION

Laser-based object-shape measurement techniques are becoming more and more popular in numerous technical domains. The most interesting areas are product inspection, reverse engineering, robot navigation, medical diagnostics and the digitalization of museum artifacts [1]. In many cases the use of non-contact methods for the measurement of shape is the only choice because of the environment, a moving object and/or a soft surface, which do not allow probe contact. An example of this is the profile inspection of an extruded rubber band in a tire-manufacturing process [2]. The temperature of the band is extremely high, the rubber is still in a semi-liquid state and, most importantly, the inspection must be conducted without any interruptions.

Laser anamorph profilometers (LAPs), which are described in this paper, are based on a laser-triangulation technique. The range information is gathered by projecting a laser plane onto the surface and imaging this line through an anamorph lens. The imaged line is curved in accordance with the measured profile of the surface because of the distance between the camera and the projector.

Posebnost našega profilomera je anamorfni objektiv, ki daje različni optični povečavi v navpični in vodoravni smeri. Anamorfna optika je ustreznejša od običajne sferične optike predvsem v primerih zahtev po velikem merilnem območju v eni smeri in veliko ločljivostjo ter manjšim merilnim obsegom v drugi smeri. Z izbiro ustreznih optičnih povečav v posamezni smeri lahko dosežemo optimalno razmerje med merilnim obsegom in natančnostjo merilnika. Takšno optiko so za potrebe laserske profilometrije med prvimi uporabili Blais s sodelavci [3], neodvisno od njih pa smo za potrebe profilometrije razvili anamorfne objektive pri nas [2].

Bistvenega pomena za uporabnost merilnika je ustrezen postopek umeritve. Glavni vodili pri snovanju le tega sta natančno merjenje referenčih točk ter ustrezen model preslikave. Ta mora upoštevati optične popačitve, hkrati pa omogočati neposreden izračun parametrov brez predhodnega poznavanja začetnih približkov. Doslej znani načini merjenja referenčne geometrije so zapleteni zaradi zahtevne izdelave etalonov in zaradi potrebe po premikanju v več smereh ([3] do [5]). Prav tako je zapletena tudi preslikava dvorazsežne slike, ki jo posname kamera, v prostor. V ta namen večina avtorjev uporablja nelinearne fotogrametrične modele [4] do [6], ki so neprimerni za preslikavo z anamorfno optiko.

Da bi odpravili tovrstne težave, smo za LAP zasnovali izviren umeritveni postopek. Meritev referenčnih točk izvajamo z etalonom v obliki poševne plošče z utori trikotnega prereza. S premikanjem plošče se spreminja višina profila, medtem ko so utori namenjeni za določitev lege referenčnih točk. Polinomski model preslikave omogoča neposreden izračun parametrov, hkrati pa dopušča korekcijo popačitev in različni optični povečavi, kar je glavna značilnost anamorfne optike.

The specialty of our profilometer is the anamorph lens, which provides different magnifications of two mutually perpendicular optical axes. This means that in the case of unequal measuring ranges in the horizontal and vertical directions, the anamorph lens gives us the optimal measuring range in terms of resolution ratio. Blais et al [3] were the first to use this technology in laser profilometry; but the anamorph lenses that we need for our profilers were developed without the cooperation of Blais, nor were they influenced by him in any way [2].

An appropriate calibration procedure is an essential step in the development of a profilometer. The main guidance came from measurements of the exact reference points and an appropriate choice of transformation model, which should consider optical aberrations without using an iterative-numerical calculation of the parameters. The complicated geometry of the reference etalon and the requirements of multi-axis movement ([3] to [5]), makes existing calibration methods difficult to implement. The transformation of points from the camera's plane back to 3-D space is also complicated. Many authors use nonlinear photogrametry models [4] to [6], which are not convenient when an anamorph lens is used.

To overcome these difficulties, a unique calibration procedure was designed for our LAP. The reference-point measurement is performed using an inclined, shaped etalon with triangular grooves. Moving the etalon in a direction perpendicular to the laser plane changes the height of the measured profile, and the transverse position of the reference points is determined with grooves. A polynomial model enables a straightforward calculation of the parameters using linear algebra, as well as correction of the various optical aberrations and magnifications for each optical axis, which is the basic property of an anamorph lens.

1 OPIS SISTEMA

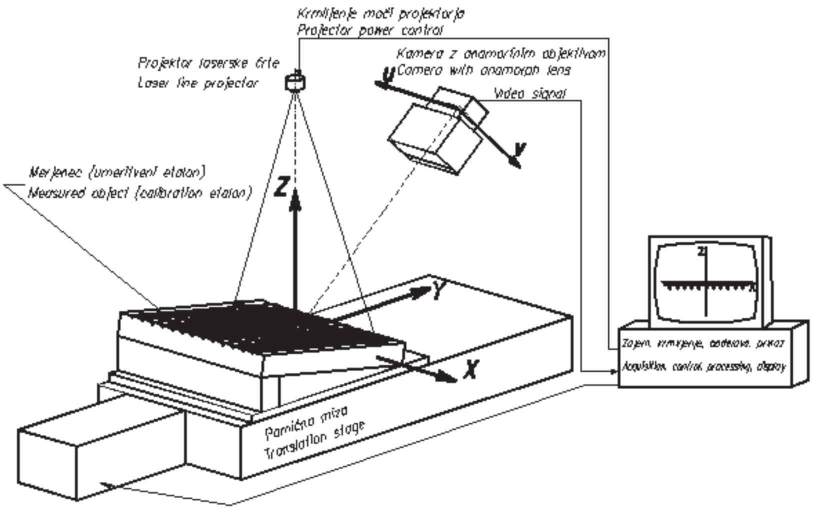
Razporeditev laserskega profilomera je prikazana na sliki 1. Sestavljen je iz projektorja laserske črte, kamere CCD z anamorfnim objektivom, pomične mize in osebnega računalnika, ki iz zajete video slike izračuna obliko profila. Računalnik krmili tudi pomično mizo ter moč projektorja, s čimer je omogočeno zaporedno merjenje profilov prek celotne površine ter optimalno delovanje na površinah s spremenljivo optično odbojnostjo.

V nadaljevanju se bomo sklicevali na skupni koordinatni sistem (SKS - WCS) ter koordinatni sistem slike (KSS - ICS). Lega SKS (X,Y,Z) je takšna, da se ravnina Y=0 ujema s svetlobno ravnino, os Z se ujema z optično osjo projektorja, izhodišče pa ima v presečišču svetlobne ravnine z optično osjo objektiva. KSS se ujema z ravnino CCD-ja, os *u* je vzporedna z vrsticami, os *v* pa s stolpci CCD-ja. Usmeritev merilnika glede na pomično mizo je takšna,

1 SYSTEM DESCRIPTION

The configuration of the LAP is shown in Figure 1. It is composed of a laser line projector, a CCD camera with an anamorph lens, a translation stage and a personal computer, which acquires video frames and then calculates the profiles from them. The computer also controls the translation stage and the projector power, which enables repeated scanning of the entire surface and optimal performance on surfaces with variable reflectance.

In the text that follows we will refer to the world coordinate system (WCS) and the image coordinate system (ICS). The orientation of the WCS (X,Y,Z) is such that the plane Y=0 is coincident with the light plane and its origin lies where the light plane and the camera's optical axis intersect. The ICS lies on the CCD plane, the axis *u* is parallel with the CCD rows and the axis *v* with the image columns. The orientation of the measure ment with respect to the



Sl. 1. *Poglavitni elementi laserskega anamorfnega profilomera ter njihova postavitev*
Fig. 1. *The main elements of a laser anamorph profilometer and their setup*

da je optična os projektorja normalna na površino mize, le-ta pa se giblje v smeri normalno na svetlobno ravnino.

1.1 Anamorfna preslikava

Uporaba anamorfnih optičnih sistemov je dandanes na nekaterih področjih izredno razširjena. Njihova bistvena lastnost sta različni optični povečavi v glavnih, medsebojno pravokotnih smereh slike. Astigmatizem, ena izmed mogočih napak človeškega očesa, ki nastane zaradi nesimetrične oblike roženice, se odpravlja z uporabo sferocilindričnih ali celo toroidnih leč. Optika polprevodniških laserjev je lahko prav tako anamorfna. Svetlobni snop polprevodniških laserjev je zaradi oblike resonatorja divergentno nesimetričen. Z uporabo prizmatičnih ali cilindričnih optičnih elementov pa je mogoče doseči okrogel laserski snop namesto običajnega eliptičnega. V primeru potrebe po svetlobni ravnini je nesimetričnost svetlobnega snopa celo zaželena. Z uporabo ene same cilindrične leče zbiramo svetlobo le v smeri najmanjše divergence, v drugi smeri pa se širi nepopačeno naprej. Takšen način oblikovanja svetlobne ravnine uporabljamo med drugim v naših profilomerih.

V našem primeru smo uporabili anamorfni objektiv z namenom prilagoditve merilnega obsega danim zahtevam. S tem je bolje izkoriščena površina zaznavnega elementa - CCD-ja ter zaradi tega izboljšana ločljivost merilnika. Anamorfni objektiv sestavljata dve medsebojno pravokotno cilindrični leči. Prva daje sliko v smeri *v*, druga pa v smeri *u*. Na sliki 2 je prikazano načelo triangulacijskega merjenja z uporabo anamorfnega objektiva. Točka T leži na ravnini laserske svetlobe in se skozi objektiv preslika v točko T’ na ravnini CCD-ja. Upoštevajoč znane geometrijske parametre dobimo naslednjo odvisnost za koordinato *z*:

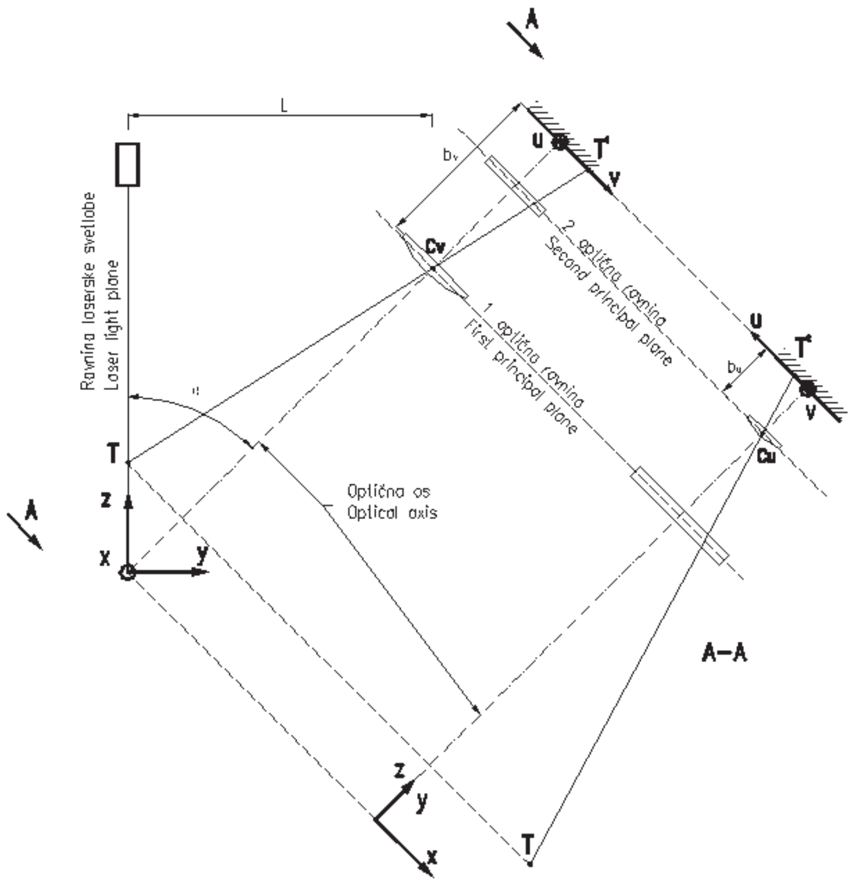
translation table is such that the projector’s optical axis is perpendicular to the translation table, which moves perpendicularly to the light plane.

1.1 Anamorph image formation

Anamorph optical systems are nowadays widely used in some fields. Their main property is a range of optical magnifications along mutually perpendicular meridians. Astigmatism, a defect of the human eye, can be corrected with sphero-cylindrical or even torically shaped lenses. Diode-laser optics can also have an anamorph optical system. They have a divergent asymmetric output due to diffraction effects in the asymmetric region of the laser cavity. Prisms or cylindrical optics are used to project a circular laser beam instead of the usual elliptical one. The divergent asymmetric output of semiconductor lasers is even desired in the case of light-plane formation. A single cylindrical lens is used to focus light in the direction of lower divergence. Such a principle of light-plane formation is also used in our profilometers.

In our case the anamorph lens is used to fit the measuring range to the camera’s sensor area. In this way the sensor area is used more efficiently and, as a result, the resolution is improved. An anamorph lens is comprised of two, mutually orthogonal cylindrical lenses. The first one forms the image in the *v* direction and the second one in the *u* direction. Figure 2 shows the image formation and triangulation principle using an anamorph lens. Point T, which lies on the light plane, is transformed through the lens at point T’ on the sensor’s plane. According to known geometrical parameters, we get the following relationship for the *z* coordinate:

$$z = \frac{L \cdot v}{\sin^2(\phi) \cdot \left(b_v + \frac{v}{\tan(\phi)} \right)} \qquad (1)$$



Sl. 2. *Načelo triangulacijskega merjenja z uporabo anamorfnega objektiva*
Fig. 2. *The principle of a triangulation-based measurement using an anamorph lens*

in za koordinato *x*: / and for coordinate *x*:

$$x = \left[\frac{L \cdot b_v}{\sin(\phi) \cdot \left(b_v + \frac{v}{\tan(\phi)} \right)} + (b_v - b_u) \right] \cdot \frac{u}{b_u} \tag{2}$$

Pri tem pomenita člena v oklepaju oddaljenost točke T od prve optične ravnine ter razdaljo med prvo in drugo optično ravnino anamorfnega objektiva.

The parts in the square brackets represent, firstly, the distance between point T and the first principal plane, and, secondly, the distance between the first and the second principal plane of the anamorph lens.

1.2 Podtočkovna zaznava laserske črte

Digitalizirano sliko obravnavamo kot množico stolpcev, kjer je vsak stolpec prečni prerez skozi intenzitetni profil laserske črte. Tako predstavlja koordinata *u* indeks posameznega stolpca, koordinata *v* pa lego črte v posameznem stolpcu.

Zaznava laserske črte poteka z uporabo algoritma podtočkovne zaznave, pri čemer izrabimo poznavanje prečnega intenzitetnega profila črte, ki ga ponazorimo z Gaussovo funkcijo. Črta v posameznem stolpcu slike leži na mestu ničle prvega odvoda intenzitete signala, ki ga izračunamo kot konvolucijo med intenzitetnim signalom v posameznem stolpcu ter odvodom Gaussove funkcije:

1.2 Sub-pixel laser-line detection

We treat the digitized image as a number of columns, where each column represents the cross-section of a laser-stripe intensity profile. In this way the *u* coordinate represents the index of each column and the *v* coordinate represents the position of a stripe in each column.

Recognition of the laser stripe is based on sub-pixel line detection, where the intensity cross-section profile of a stripe is approximated by means of a Gaussian function. In this case the stripe in each column lies at the point where the first derivative of the intensity profile (also the signal) equals zero. The latter is calculated using a convolution between the intensity signal in each column and the first derivative of the Gaussian function:

$$I'_j = \sum_{k=-N_k}^{N_k} I_{j+k} \cdot K_k \qquad (3),$$

pri čemer je K_k element konvolucijskega jedra, ki ima obliko prvega odvoda Gaussove funkcije:

where K_k is the element of the convolution kernel, which is expressed by means of the first derivative of the Gaussian function:

$$K_k = \frac{k}{s^3} \cdot e^{-\frac{k^2}{2s^2}} \qquad (4),$$

N_k je polovična širina konvolucijskega jedra in s širina Gaussove funkcije, ki je približno enaka polovični širini laserske črte.

Ker je intenzitetni signal vzdolž stolpcev slike diskreten, izračunamo ničlo odvoda signala z linearno interpolacijo med sosednjima točkama, izmed katerih ima predhodna pozitivno, naslednja pa negativno vrednost.

N_k stands for the half-width of the convolution kernel and s stands for the width of the Gaussian function, which is approximately equal to the laser-stripe half-width.

Since the intensity signal along the column picture is discrete, the zero of the first derivative can be calculated using a linear interpolation between two neighboring points, where the former is positive and the latter is negative.

2 UMERITEV

2 CALIBRATION

Umeritveni postopek pomeni določitev relacije med KSS in SKS . Postopek obsega merjenje referenčnih točk ter izračun parametrov modela preslikave, ki matematično popisuje zgoraj omenjeno odvisnost. Seveda je najprej treba izbrati ustrezen model preslikave.

In the calibration procedure we determine the relationship between the ICS and the WCS. The procedure consists of a reference-point measurement and a calculation of the parameters of the transformation model, which mathematically describes the previously mentioned relationship. Of course, this model must be determined prior to the calibration.

2.1 Polinomski model preslikave

2.1 Polynomial model of transformation

Ker je lega SKS izbrana tako, da merjeni profil površine leži na ravnini Y=0, preslikava poteka med dvema dvorazsežnima koordinatnima sistemoma, ki ju popišemo s polinomskim modelom preslikave:

Since the position of the WCS is such that the measuring profile lies on the plane Y=0, the transformation goes between two two-dimensional coordinate systems, which we describe using a polynomial model of transformation:

$$x = \sum_{j=0}^{M-1} \sum_{i=0}^{N-1} A_{j,i} \cdot u_f^{\,i} v_f^{\,j} \qquad (5)$$

$$z = \sum_{j=0}^{M-1} \sum_{i=0}^{N-1} B_{j,i} \cdot v_f^{\,i} u_f^{\,j} \qquad (6).$$

Elementi $A_{j,i}$ in $B_{j,i}$ pomenijo utežne faktorje za posamezne člene polinomov. Zbrani so v tako imenovanih korekcijskih matrikah A in B. S prvimi členi obeh polinomov popravimo odmik in povečavo, s členi višjih redov pa popačitve objektiva ter nelinearnost triangulacijskega merjenja.

Dobra lastnost tega modela se izkaže predvsem pri izračunu korekcijskih matrik, saj omogoča neposreden izračun. Tako lahko ob poznavanju koordinat referenčnih točk v SKS *(Xref in Zref)* ter v KSS (*Uref* in *Vref*) izračunamo vrednosti elementov obeh matrik po metodi predoločenega sistema linearnih enačb [7].

Elements $A_{j,i}$ and $B_{j,i}$ stand for the weights of each polynomial element. They are grouped in the so-called calibration matrixes *A* and *B*. The translation and magnification in each axis are adjusted using the first two elements, since lens distortions and nonlinearity related to the triangulation are corrected using higher-order elements.

The advantage of this model is clearly demonstrated in the calculation of the calibration matrixes, because it enables a straightforward calculation. When the coordinates of the reference points in the WCS (*Xref* and *Zref*) and the ICS (*Uref* and *Vref*) are known, the elements of the calibration matrixes are calculated by means of a singular-value decomposition [7].

2.2 Meritev in zaznava referenčnih točk

2.2 Measurement and detection of reference points

Referenčne točke izmerimo prek celotnega merilnega območja z uporabo umeritvenega etalona. Ta ima obliko poševne plošče z utori trikotnega

Reference points are measured over the entire measuring area using the calibration etalon. This has an inclined plate with linear grooves of a triangular prereza vzdolž osi Y. Etalon med umerjanjem pritrdimo na pomično mizo, kakor je prikazano na sliki 3. Trikotni utori so namenjeni razpoznavi lege referenčnih točk v smeri X, spreminjanje višine referenčnih točk pa je doseženo s premikanjem etalona v smeri Y, in sicer po naslednji enačbi:

shape along the Y axis. The etalon is fixed on the translation stage as shown in Figure 3. The triangle-shaped grooves are used to detect reference points along the X axis, and the change of height of the reference points is achieved by moving the etalon along the Y axis:

$$\Delta Z = \Delta Y \tan(\alpha) \quad (7).$$

Koordinate referenčnih točk v skupnem koordinatnem sistemu tako izračunamo:

The world coordinates of the reference points are calculated using the following equations:

$$Xref_{j \cdot N_x + i} = \Delta X \cdot i - X_{offset} \quad (8)$$

$$Zref_{j \cdot N_x + i} = \Delta Z \cdot j - Z_{offset} \quad (9),$$

kjer je $i = 0 \ldots N_x\text{-}1$, $j = 0 \ldots N_z\text{-}1$, N_x je število utorov, ΔX je razmik med utori in N_z število izmerjenih profilov. Odmik SKS glede na prvo referenčno točko določujeta parametra X_{offset} in Z_{offset}.

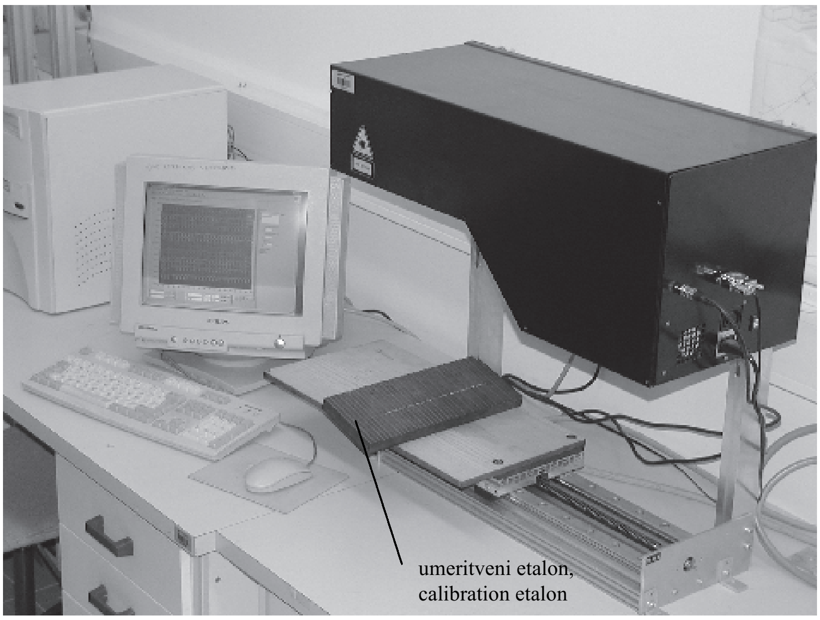
Lege referenčnih točk V ICS določimo iz niza izmerjenih profilov umeritvenega etalona. Uporabljamo naslednji postopek:

a) Določitev lege točk v smeri *u* je analogna zaznavi laserske črte v posameznem stolpcu slike: iz posnetih profilov izločimo lego zarez *(Uref)* s postopkom podtočkovne zaznave na podlagi iskanja ničle prvega odvoda višine profila.
b) Lego referenčnih točk v smeri *u* izračunamo kot povprečno višino profila v okolici posamezne točke, pri čemer zanemarimo območje zareze:

where $i = 0 \ldots N_x\text{-}1$ and $j = 0 \ldots N_z\text{-}1$, N_x is the number of grooves, ΔX is the distance between the grooves and N_z is the number of measured profiles. The offset of the WCS with respect to the first reference point defines the parameters X_{offset} and Z_{offset}.

The positions of the reference points in the ICS are determined from a series of measured profiles of the calibrating etalon. We use the following procedure:

a) Detection of the reference-point position along the *u* direction is analogous to the laser-stripe detection in each image column. In other words, the groove position *(Uref)* is detected from measured profiles using sub-pixel detection based on zero searching of the first derivative of the measured profiles.
b) The reference-point position along the *u* direction is calculated by means of the average profile height around each reference point, where the region of the groove is discarded:



Sl. 3. *Umerjanje laserskega anamorfnega profilomera*
Fig. 3. *Calibration of a laser anamorph profilometer*

$$Vref_i = \frac{1}{2(N_{out} - N_{in})} \left[\sum_{k=-N_{out}}^{-N_{in}} V_{\langle Uref_i \rangle + k} + \sum_{k=N_{in}}^{N_{out}} V_{\langle Uref_i \rangle + k} \right] \quad (10).$$

Pri tem je N_{out} polovična širina okolice povprečenja, N_{in} polovična širina utora, $\langle Uref_i \rangle$ pa je zaokrožena vrednost lege vrha zareze v smeri *u*.

where N_{out} stands for the half-width of the average neighborhood; N_{in} stands for the half-width of the groove and $\langle Uref_i \rangle$ stands for the rounded value of the groove position along the *u* direction.

3 PREIZKUSI

V tem poglavju so predstavljeni preizkusi, ki smo jih izvedli z različnimi modeli LAP-ov. Meritve pokrivajo različna področja tehnike ter tudi različne potrebe po merilnih obsegih, vsem pa je skupno, da je ena izmera profila izrazito poudarjena v primerjavi z drugo. Zaradi tega je uporaba anamorfne preslikave primernejša od običajne - sferične, kar je razvidno tudi iz predstavljenih rezultatov.

3.1 Rezultati umerjanja

Rezultati umerjanja so prikazani za LAP z naslednjimi značilnostmi:
merilno območje: 200 × 20 mm (širina × višina),
ločljivost kamere: 360 × 288 točk,
velikost zaznavala CCD: 4,6 mm × 3,4 mm,
kot triangulacije: $\phi = 45°$
pomična miza: ISERT, hod: 300 mm,
korak: 0,01 mm,
osebni računalnik: Pentium II/233MHz
Geometrijski parametri umeritvenega etalona so:
nagib plošče: $\alpha = 12{,}2°$,
razmik med utori: $\Delta X = 8{,}00$ mm,
širina utora: $W_{utor} = 3{,}00$ mm,
globina utora: $H_{utor} = 1{,}50$ mm,
material: tekstolit.

Etalon smo v smeri Y premikali po $\Delta Y = 5{,}00$ mm, kar pomeni, da je razmik med izmerjenimi profili v navpični smeri $\Delta Z = 1{,}08$ mm (glej enačbo (7)). Izmerjenih profilov je bilo $N_x = 16$, na vsakem izmed njih pa je bilo upoštevanih $N_z = 25$ utorov. Slika 4 prikazuje izmerjene profile ter referenčne točke, ki so bile določene po zgoraj opisanem postopku. Zaradi optičnih napak, predvsem ukrivljenosti polja, je na robovih merilnega območja kakovost izmerjenih profilov slabša, zaradi česar sta prvi in zadnji utor vsakega profila izvzeta iz nadaljnjega postopka.

V fazi izračuna korekcijskih matrik najprej določimo reda obeh. Reda matrike **A** 4×2 in matrike **B** 5×2 sta bila izbrana zaradi najmanjših standardnih odstopkov v posamezni smeri. Primerjava med izmerjenimi in pravimi legami referenčnih točk je prikazana na sliki 5. Že omenjeni standardni odstopek v smeri X znaša 0,076 mm in v smeri Z 0,028 mm. Tako je relativni standarni odstopek vzdolž smeri X približno 1/2600 merilnega območja, vzdolž smeri Z pa približno 1/700. Vidimo, da sta standardna

3 EXPERIMENTS

In this section we present the experiments that were made using different models of the LAP. The measurements cover different fields of the technique and also the different needs of measuring ranges, but they have a common property: that one dimension of the profile is much more stressed than the other one. Because of this, an anamorph lens is more suitable than a conventional lens, spherical, which is also evident from the results shown.

3.1 Calibration results

Calibration results are shown for the LAP with the following characteristics:
measuring range: 200 × 20 mm (width × height),
camera resolution: 360 × 288 pixels,
CCD dimension: 4.60 × 3.40 mm,
triangulation angle: $\phi = 45°$,
translation stage: ISERT, travel: 300 mm,
step: 0.01 mm,
personal computer: Pentium II/233MHz.
Geometrical parameters of the calibration etalon are:
plate inclination: $\alpha = 12.2°$,
distance between grooves: $\Delta X = 8.00$ mm,
groove width: $W_{utor} = 3.00$ mm,
groove depth: $H_{utor} = 1.50$ mm,
material: textolit.

The etalon was shifted along the Y direction by $\Delta Y = 5.00$ mm, which means that the distance between the measured profiles, ΔZ. is equal to 1.08 mm (see Eq. (7)). We examined 16 measured profiles (N_z) and 25 grooves (N_x) on each profile. Figure 4 shows the measured profiles and the reference points, which were detected according to the above procedure. The quality of the measured profiles near the image borders is somewhat poorer due to optical aberrations, especially because of field curvature, therefore the first and last groove of each measured profile were omitted from the subsequent procedure.

The first step in the calibration-matrix calculation is a determination of the matrix dimensions. The dimensions of 4×2 for matrix **A** and 5×2 for matrix **B** were chosen as optimum sizes because of the minimum achieved standard deviations in each separate direction. Figure 5 shows a comparison between the measured and the actual positions of the reference points. The standard deviations amount to 0.076 mm along the X direction and 0.028 mm along the Z direction. So, the relative standard deviation along the X direction amounts to approximately 1/2600 of the measurement range, and approximately 1/700 along the odstopka daleč manjša od ločljivosti zaznavnega elementa (360 × 288), kar kaže na natančnost umeritvenega postopka.

3.2 Nadzor profila gumijastega traku

Izvlečen gumijast trak se uporablja za izdelavo avtomobilskih plaščev in želja naročnika je bila razvoj sistema za sproten nadzor profila traku ter zančno krmiljenje orodja, s čimer bi dosegli večjo kakovost izdelkov ter zmanjšali proizvodne stroške zaradi zmanjšanja izmeta in zaustavljanja proizvodnje.

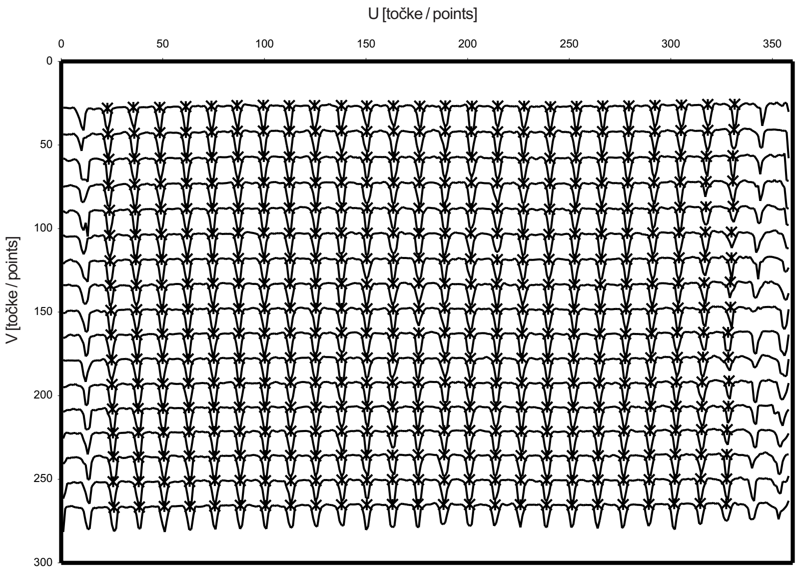
Profilomer ima značilnosti, kakršne so navedene v prejšnjem poglavju. Optika je prilagojena

Z direction. We see that both standard deviations are much smaller than the camera resolution (360 × 288), which shows in the exactness of the callibration procedure.

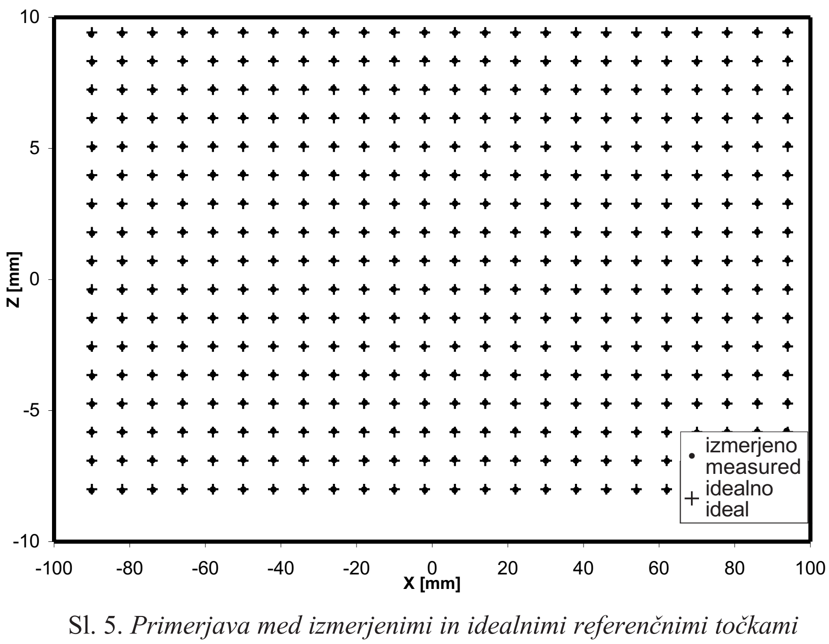
3.2 Inspection of the extruded rubber-band profile

The extruded rubber band is used in the tire manufacturing process and the manufacturer's needs were to develop a system with real-time inspection of the extruded band profile. With such feedback control of the extruder, better production quality and lower production costs are ensured as a result of reduced levels of waste and uninterrupted production.

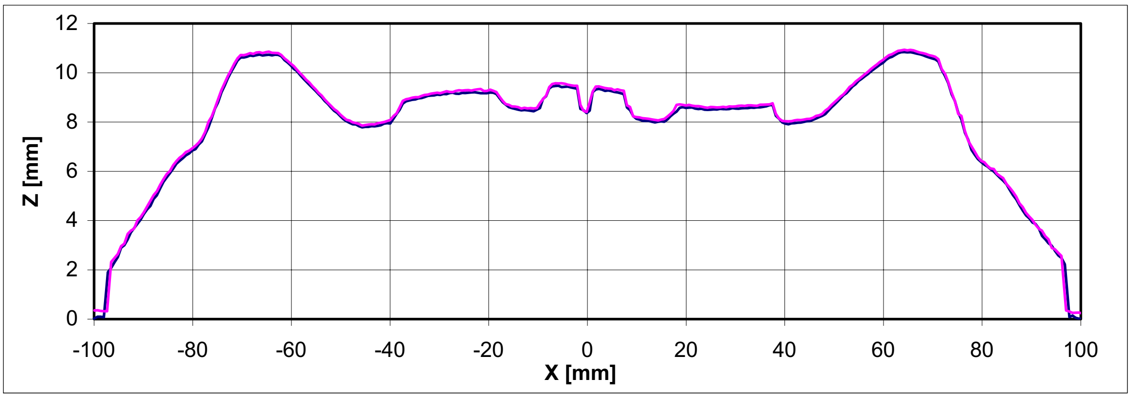
The profilometer has the same characteristics as those listed in the previous section. The optics



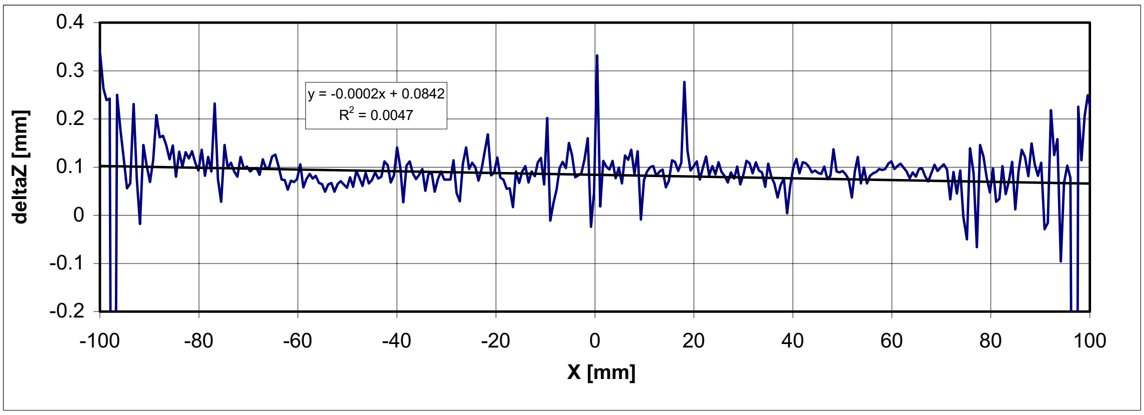
Sl. 4. *Izmerjeni profili umeritvenega etalona ter referenčne točke (×)*
Fig. 4. *Measured profiles of the calibration etalon and the detected reference points (×)*



Sl. 5. *Primerjava med izmerjenimi in idealnimi referenčnimi točkami*
Fig. 5. *Comparison between the measured and the ideal reference points*



Sl. 6. *Profila izvlečenega gumijastega traku. Pred drugo meritvijo je bil trak podložen s tankim papirjem.*
Fig. 6. *Two profiles of an extruded ruber band. The band was lined with a sheet of paper, before the second measurement.*



Sl. 7. *Razlika med profiloma gumijastega traku, ki sta prikazana na sliki 6.*
Fig. 7. *Difference between the two profiles that are shown in figure 6.*

gabaritom prereza izvlečenega traku (širina in višina), ki se gibljejo od *150* × *13* mm (širina × višina) do *200* × *18* mm. Temu primerno je tudi merilno območje inštrumenta, ki znaša *200* × *20* mm.

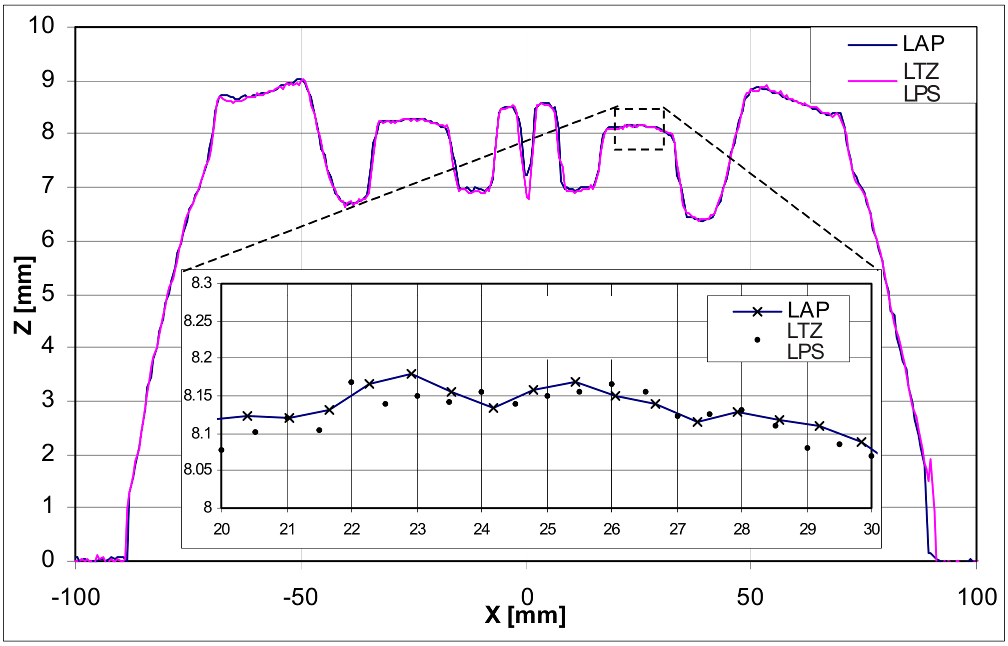
Na sliki 6 sta prikazana dva prečna profila istega traku, ki je enkrat dvignjen za debelino lista papirja (*~0,1* mm). Slika 7 prikazuje razliko izmerjenih višin vzdolž profilov. V idealnem primeru bi morala razlika biti v vseh točkah enaka, vendar zaradi različnih motilnih vplivov temu ni tako. Do največjih odstopanj prihaja na robovih merilnega območja zaradi že omenjenih optičnih nepopolnosti objektiva. Precejšnji odstopki so tudi na mestih velikega nagiba profila, pri čemer gre vzrok iskati predvsem v slabši vidljivosti teh področij. Kljub vsem omenjenim nepopolnostim je iz zgornjih dveh grafov razvidno, da je ločljivost profilomera na dejanskih objektih manjša od 0,1 mm.

Majhno merilno negotovost in kakovosten umeritveni postopek potrjuje tudi vzporedno opravljena meritev profila izvlečenega gumijastega traku s trgovskim točkovnim triangulacijskim zaznavalom. Uporabili smo zaznavalo proizvajalca MEL - Mikroelektronik GmbH. Zaznavalo z oznako

are adapted to the dimensions of the extruded band section, which ranges from *150* × *13 mm* (width × height) to *200* × *18 mm*, so the measuring range of the instrument equals *200* × *20 mm*.

Figure 6 shows two profiles of the same rubber band, first in its neutral position and then in a slightly lifted position (*~0.1 mm*). Figure 7 shows the height difference along these two profiles. In the case of an ideal measurement the difference would be constant over the entire length; however, due to various disturbing impacts the real difference is not constant. The largest deviations occur at the edges of the measuring range due to the already mentioned optical imperfections of the lens. Considerable deviations also exist in places where the profile is very steep, because of the poorer visibility in these places. In spite of all these imperfections, it is evident from the above figures that the profiler's resolution on a real object is less than 0.1 mm.

A small measurement uncertainty and a successful calibration method were also confirmed by the measurement of the same band cross-section using a commercial point-triangulation sensor. The manufacturer of this sensor is MEL - Mikroelektronik gmbh, the sensor type is M5L/10, the measuring range



Sl. 8. *Profil izvlečenega gumijastega traku, izmerjenega z laserskim anamorfnim pofilomerom (LAP) ter laserskim točkovnim zaznavalom (LTZ)*

Fig. 8. *Pofile of the extruded ruber band, measured first with a laser anamorph profilometer (LAP) and second with a laser-point sensor (LPS)*

M5L/10 ima merilno območje ±5,0 mm, napaka linearnosti znaša 30 µm in naključni odstopek 3 µm [8]. Izmerjenih je bilo 400 točk vzdolž profila, kar je približno enako prečni ločljivosti profilomera. Na sliki 8 je razvidno dobro ujemanje obeh izmerjenih profilov. Iz povečave na sliki 8 je razvidno, da je velikost odstopkov primerljiva pri obeh meritvah. To pomeni, da na dejanskem vzorcu dosegamo enako merilno negotovost, kakršno ima trgovsko točkovno zaznavalo, vendar ob mnogo krajšem času meritve. V primeru točkovnega senzorja je čas znašal približno 3 minute, v primeru profilomera pa ~0,5 sekunde!

Tako lahko rečemo, da sistem izpolnjuje prvotno zastavljen cilj tako glede natančnosti kakor tudi hitrosti merjenja.

3.3 Nadzor postopka laserskega odstranjevanja barve

Dandanes znaša letna svetovna potreba po čiščenju barvanih ali oksidiranih površin nekaj sto milijonov kvadratnih metrov. Sem spadajo površine letal, ladij in drugih konstrukcij [9]. Temu primerno dejaven je tudi razvoj novih tehnologij čiščenja, kjer se poleg običajnih postopkov, med drugim vedno bolj uveljavlja lasersko čiščenje. Ta tehnika ima pred običajnimi postopki vrsto prednosti, izmed katerih sta najpomembnejši selektivno odstranjevanje materiala (vrsta in lokacija) ter ekološka neoporečnost postopka ([9] in [10]).

Z namenom optimiranja parametrov ter izvedbe nadzora postopka laserskega odstranjevanja barvnih oziroma oksidnih plasti potekajo v

is ±5.0 mm, the nonlinearity error equals 30 µm and the resolution (noise level) equals 3 µm [8]. The profile was measured at 400 points, which is approximately equal to the transverse resolution of our profilometer. Figure 8 shows that both profiles fit very well. It is clear from the magnification on Figure 8 that the deviations of both measurements are of the same order. This means that the profilometer has the same measurement uncertainty on a real object as the above commercial point sensor has. But the time for measuring the profile using the point sensor was ~3 minutes, whereas with the profilometer this time was only ~0.5 seconds!

It is clear that the system fulfills the requirements as far as accuracy and measuring speed are concerned.

3.3 Monitoring of the laser-based decoating process

Nowadays, worldwide decoating needs are enormous: each year several hundred million square meters of surfaces have to be stripped. These surfaces mainly belong to airplanes, boats and other constructions [9]. As a result there are a lot of new stripping techniques being developd. Besides conventional methods, laser-based decoating processes have been gaining wide acceptance in recent years. These processes have many advantages, among which the most important are selectivity (material and location) and reduced environmental impact ([9] and [10]).

To optimize the parameters and monitor the laser-based decoating of colored layers, research in this field is taking place in the Group for

Laboratoriju katedre za optodinamiko in lasersko tehniko raziskave na tem področju [11]. Eksperimentalna postavitev (sl. 9) omogoča sprotno merjenje optodinamskih signalov (v nadaljevanju OD) vzbujenih ne le v podlagi, ampak tudi v okoliškem zraku, hkrati pa omogoča tudi merjenje geometrijske oblike nastajajočega kraterja po vsakokratnem laserskem blisku. Naloga te študije je v prvi fazi poiskati povezavi med značilkami OD signalov in količino odvzetega materiala ter značilkami OD signalov in zaustavitvijo odstranjevanja. V ta namen smo med drugim razvili laserski anamorfni profilomer z ustreznimi značilnostmi, ki je namenjen kot referenčni merilnik geometrijske oblike nastajajočega kraterja.

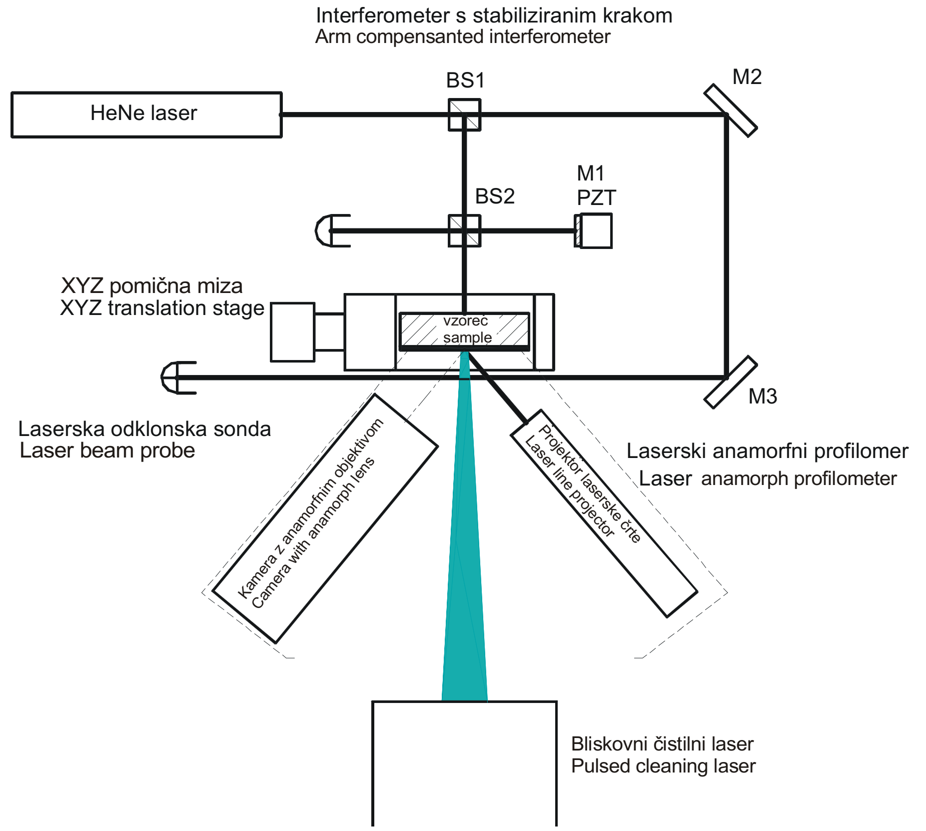
Geometrijska oblika omenjenega kraterja je izmerjena po vsakokratnem laserskem blisku. Pomik prečno na merjeni profil, tako imenovano snemanje (skaniranje), je zagotovljeno z računalniško krmiljeno mikropozicionirno mizico za premikanje obdelovanca. Anamorfni objektiv in laserski projektor sta zasnovana tako, da merilno območje LAP znaša *20 × 3 × 25* mm (širina × višina × gib mizice). Za snemanje laserske črte smo uporabili digitalno kamero CCD ADIMEC 12XP z ločljivostjo *1024 x 1024* točk, izmerami zaznavalnega elementa *10 x 10* mm ter dinamičnim obsegom *12* bit.

Slika 10 prikazuje potek odstranjevanja plasti barve prek sredine kraterja. Lepo je razvidno enakomerno naraščanje globine prek celotnega števila bliskov vse do konca odstranjevanja. Zanimivo je,

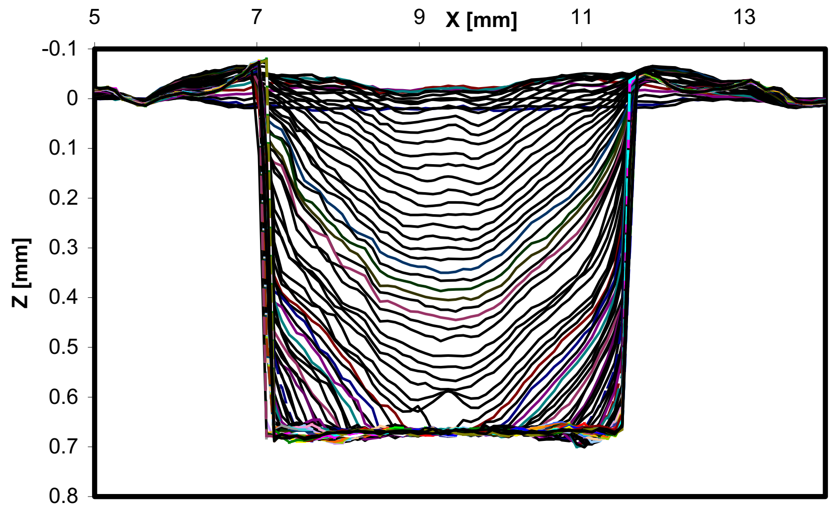
Optodynamics and Laser Applications [11]. The experimental setup that is shown in Figure 9 enables a real-time measurement of optodynamic signals (ODs), which are induced not only in the substrate but also in the surrounding air; and it also enables geometry measurements of the growing crater after each laser pulse. The aim of this study was to find two kinds of correlations: first, between the significant features of the optoacoustic signal and the amount of ablated coating; and second, between the significant features of the optoacoustic signal and the termination of the cleaning process. A laser anamorph profiler with appropriate characteristics was developed specifically for a reference measurement of the geometry of the growing crater.

The geometry of the crater is measured after each laser pulse. Movement across the crater area, known as scanning, is possible due to a computer-controlled micro-positioned translating stage. The anamorph lens and the laser projector are designed to achieve a measuring range of *20 × 3 × 25 mm* (width × height × stage travel). The ADIMEC 12XP digital CCD camera has a *1024×1024 pixel* resolution, a *10×10 mm* CCD dimension and a *12-bit* dynamic range.

Figure 10 shows the progress of the colored layer decoating through the middle plane of the crater. Constant linear deepening is clearly visible over the entire process. It is interesting that at the beginning

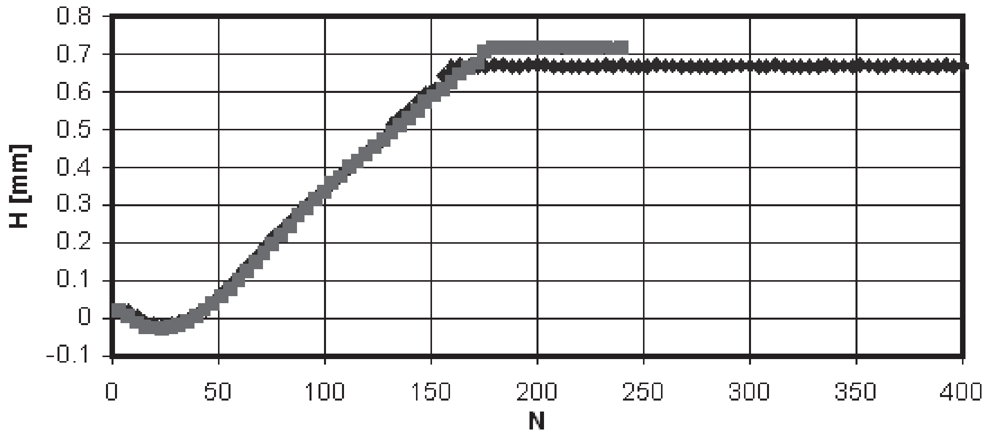


Sl. 9. *Shema merilne verige za nadzor postopka laserskega čiščenja*
Fig. 9. *Experimental setup for monitoring the laser decoating process*



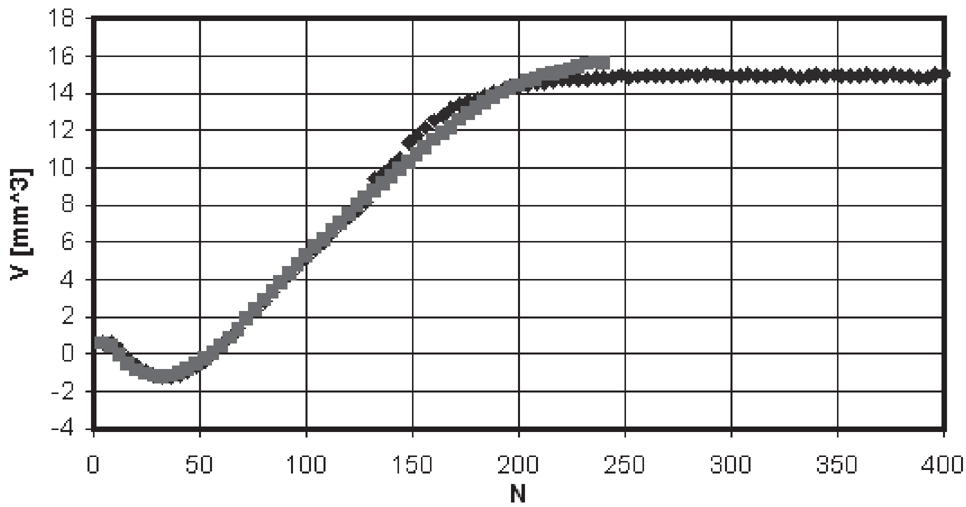
Sl. 10. *Napredovanje odstranjevanja plasti barve med postopkom laserskega čiščenja Prikazani so srednji profili kraterja po vsakem četrtem laserskem blisku.*

Fig. 10. *Progress of colored-layer decoating during the laser cleaning process. The figure shows the middle profile of the crater after every fourth laser pulse.*



Sl. 11 *Naraščanje globine kraterja v odvisnosti od števila bliskov med laserskim odstranjevanjem plasti barve (♦ meritev 1, ■ meritev 2)*

Fig. 11. *Increase in the depth of the crater with the number of laser pulses during laser decoating (♦ measurement 1, ■ measurement 2)*



Sl. 12. *Naraščanje prostornine odstranjene barve v odvisnosti od števila bliskov med laserskim odstranjevanjem plasti barve (♦ meritev 1, ■ meritev 2)*

Fig. 12. *Increase in the volume of the crater with the number of laser pulses during laser decoating (♦ measurement 1, ■ measurement 2)*

da na začetku postopka površina rahlo nabrekne, kar pripisujemo spreminjanju kemične sestave barvne plasti. Začetno nabrekanje in nadaljnje enakomerno odstranjevanje barve je razvidno tudi iz diagramov na slikah 11 in 12, ki prikazujeta večanje globine kraterja in prostornine odstranjene plasti barve v odvisnosti od števila laserskih bliskov. Diagrama prikazujeta dve meritvi na enakem vzorcu barve. Razvidna je dobra ponovljivost postopka tako z vidika hitrosti odstranjevanja kakor tudi z vidika začetnega nabrekanja. Različni končni globini kraterja pa nista posledici merilne negotovosti, ampak neenakih debelin barvnih plasti.

4 SKLEPI

V prispevku opisujemo delovanje in razvoj laserskih anamorfnih profilomerov ter dva primera uporabe, pri katerih se izkaže anamorfna profilometrija primernejša od običajne krogelne. Poseben pomen pripisujemo inovativni metodi umerjanja. Namesto fotogrametričnega modela vpeljemo polinomski model preslikave, katerega parametri so v obliki korekcijskih matrik preprosto izračunljivi. Odmik in povečavo uravnavata prva dva člena, nelinearnosti zaradi optične popačitve ter triangulacije pa višji členi omenjenih matrik. Prav tako izviren je postopek merjenja referenčnih točk. Umeritveni etalon ima obliko poševne ploščе z vzdolžnimi utori trikotnega prereza. S preprosto reliefno površino, ki je ni težko natančno izdelati, je dosežena natančna določitev lege referenčnih točk v vodoravni in navpični smeri. Vse našteto prispeva k preprosti in čvrsti izvedbi umeritvenega postopka, zaradi česar ga je mogoče hitro izvesti po vsakem poseganju v geometrijsko obliko merilnika.

Primera uporabe v prvi vrsti dokazujeta uporabnost laserske anamorfne profilometrije na različnih področjih tehnike ter tudi različne potrebe po merilnih obsegih. V obeh primerih je ena izmera merilnega obsega izrazito poudarjena v primerjavi z drugo. Zaradi tega je uporaba anamorfne preslikave primernejša od običajne sferične, kar je razvidno tudi iz predstavljenih rezultatov.

of the process the surface swells slightly, which we attribute to chemical changes in the colored layer. The initial swelling and the subsequent linear deepening can also be seen on the graphs in Figures 11 and 12, which show the increase of the crater depth and the volume of removed color with respect to the number of laser pulses. Two measurements of the two craters are shown on the same color layer. It is evident that the repeatability of the process is good, which goes not only for the decoating rate but also for the initial swelling of the surface. The different final crater depths are not a consequence of the measurement uncertainty, but of the unequal thickness of the colored layer.

4 CONCLUSIONS

In this paper we describe the principles and development of laser anamorph profilometers. We give particular emphasis to the novel calibration method. We introduce a polynomial model of the transformation instead of the photogrametry model, which enables us to compute the model parameters (the so-called calibration matrixes) more easily by means of linear algebra. The translation and magnification in each optical axis are adjusted using the first two elements, since lens distortions and nonlinearity related to triangulation are corrected by the use of higher-order elements of the matrixes. The measurement of the reference points is also original, since the callibration etalon has an inclined surface with linear grooves of triangular shape along the Y axis. An accurate determination of the reference-point positions is achieved with simple etalon relief, which is easy to make. All these factors contribute to a simple and robust realization of a calibration procedure. Because of this the procedure can be conducted at any time, especially after each change of profilometer geometry.

Both experiments demonstrate the applicability of laser anamorph profilometry in different fields of the technique, where one dimension is much more emphasised than the other one. Because of this, an anamorph lens is more suitable than a conventional, spherical one.

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Naslov avtorjev: Matija Jezeršek
prof.dr. Janez Možina
Fakulteta za strojništvo
Univerza v Ljubljani
Aškerčeva 6
1000 Ljubljana
matija.jezersek@fs.uni-lj.si
janez.mozina@fs.uni-lj.si

Authors' Address: Matija Jezeršek
Prof.Dr. Janez Možina
Faculty of Mechanical Eng.
University of Ljubljana
Aškerčeva 6
1000 Ljubljana, Slovenia
matija.jezersek@fs.uni-lj.si
janez.mozina@fs.uni-lj.si

Prejeto:
Received: 6.12.2002

Sprejeto:
Accepted: 29.5.2003

Odprt za diskusijo: 1 leto
Open for discussion: 1 year